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ORIGINAL ARTICLE

Analysis of tool vibration and surface roughness with tool wear progression in hard turning: An experimental and statistical approach

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ABSTRACT – The machined surface quality and dimensional accuracy obtained during hard turning is prominently gets affected due to tool wear and cutting tool vibrations. With this view, the results of tool wear progression on surface quality and acceleration amplitude is presented while machining AISI 52100 hard steel. Central Composite Rotatable Design (CCRD) is employed to develop experimental plan. The results reported that vibration signals sensed in a tangential direction (V_z) are most sensitive and found higher than the vibrations in the feed direction (V_x) and depth of cut direction (V_y). The acceleration signals in all three directions are observed to increase with the advancement of tool wear and good surface finish is observed as tool wear progresses up-to 0.136mm. The vibration amplitude is discovered high in the range 3 kHz – 10 kHz within selected cutting parameter range (cutting speed 60-180mm/min, feed 0.1-0.5mm/rev, depth of cut 0.1-0.5mm). The investigation is extended for the development of multiple regression models with regression coefficients value 0.9. These models found statically significant and give dependable estimates between a tool vibrations and cutting parameters.

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INTRODUCTION

Materials of hardness range within 46-68 HRC are designated as material of high hardness; these include various case-hardened steels, hardened alloy steels and high-speed steels. These materials are preferred for their exceptional mechanical properties like high hardness; high wear opposition. These materials are extensively used in applications like chain sprocket, steel ball bearings, transmission shaft, valve casing, engine parts, gears, bearing, dies, punches, nozzles, railways components, helicopter camshaft [1-2]. The conventional processes for turning hardened steel are electric-discharge and grinding; and are in limited is use due to high tooling cost, low surface finish and material removal rate, faster wear. To overcome these drawbacks, these materials are turned with the super-hard cutting tools and process is referred as hard turning [3-4]. It is reported that this process is performed with no cooling media. This reduces post processing of cutting fluid in terms of its storage and dumping, and also decreases part cost up to 70% [5-6]. But some analysts support utilization of cooling media in view of better surface finish and low tool vibrations [7-8].

Nowadays, carbide tools with the diverse coatings are utilized as a option for PCBN and ceramics tools. The much of the time utilized coatings incorporate TiN, TiAlN, TiCN, TiAlCN Al_2O_3[9-13]. The performance of cutting tool with and without coatings in terms of cutting force [3-4], surface roughness [9-13], chip morphology [15] and acoustic emission [16] with various grades of the cutting tools is studied by different researchers and in-depth review related process parameter is reported by Ambhore et al. [17].

In hard turning, development of wear at the cutting edge of tool is the major drawback. The worn cutting edge develops more contact with the workpiece and thus increases friction between tool and workpiece. It results in more power consumption and induces vibrations during the cutting process. [18]. Forced vibration, is due to certain periodical forces that exist inside the machine that might be because of faulty gear drives, misalignment, unequal machine-device components and, so on. Vibrations in the metal cutting process are because of various attributes of the process such as varying cutting condition [11-12]. Self-excited vibrations are induced due to interaction between chip evacuation process and machine tool structure; and are considerably harming to a finished surface and results in drastic reduction in tool life. Non-homogeneity of workpiece material and improper system stiffness can brought more vibrations and noise in machining environment. The tool vibrations produce unacceptable part surface quality and unpredictable tool failure [18-19]. Therefore such processes and associated vibrations are to be investigated deliberately.

The direct measurement of cutting tool vibration is difficult, hence related vibration parameters such as acceleration, velocity, displacement etc. are measured with the help of sensors. Piezoelectric accelerometers are widely used because of its very high dynamic range, high sensitivity and ability to operate at higher temperature. The nature of measured vibration is complex comprising various time dependable sinusoidal waves. Analysis of such response in frequency domain is extremely valuable since every parts of signal are more promptly revealed. The breaking of a complex signal into various sinusoidal components is achieved by transforming signals from time domain to frequency using Fast Fourier Transform analyzer [15]. Other techniques such as root mean square (RMS)[15], support vector machine[16], singular

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spectrum analysis (SSA)[8,20], etc are also used to analyze the vibration signals. FFT and RMS techniques have received a wide popularity among the researchers because of its fast data processing ability.

Zahia et al. [11] inferred that feed is overwhelming component impacting surface harshness, while vibrations in radial and tangential discovered an irrelevant impact on surface unpleasantness in turning 42CrMo4 hardened steel. Upadhyay et al. [12] investigated cutting tool acceleration in machining Ti-6Al-4V steel for in-process forecast of surface roughness. The in-process conjecture model discovered reliable with R^2 esteem 0.93. It is presumed that the feed is extraordinary effect on surface unpleasantness that spiral bearing increasing speeds. Grynal et al. [21] reported that flank wear is extraordinarily affected by machining factors. This investigation reasoned that surface is significantly affected by machining factors. The expansion in flank wears drives improvement in surface completion.

Bhuiyan et al. [15] captured vibration response while machining steel material ASSAB-705. The RMS vibration amplitude in directions namely feed and tangential has rational response to the flank wear progression. The increasing trend in vibration acceleration is observed as cutting speed increases. Prasad et al. [22] exhibited an inter-relationship between tool displacement and hardness. R^2 value of developed model is observed 0.9. The ANOVA reported that tool displacement parameter is affected by depth of cut, cutting rate and material hardness.

In machining of high hardness steel using carbide coated tool, the majority of the investigations are found in associating surface harshness with tool vibration. However, the literature in correlating vibration with tool wear is hardly reported for hard turning. The objectives of the present study are to explore variation of tool vibration signals with the advancement of tool wear and, to perform analysis of variance for development of empirical relations. This investigation imparts the understanding of impact of cutting parameters on vibration signals and tool wear in turning hardened AISI52100 steel using low-cost PVD coated carbide tool.

EXPERIMENTAL PROCEDURE

Workpiece and Tool material

The trails are executed on AISI52100 alloy steel cylindrical bar. The length and diameter was 60mm and 460mm respectively. The hardness 54±2 HRC is accomplished with help of heat treatment process. Then the rod is cleaned and put in to the machining environment. The insert is chosen based on tool maker's catalogue, workpiece hardness, and tool cost. The suitable grade is suggested as CNMG 120408 with tool holder PCLNR-25-25 M12. This is high quality insert of coating TiSiN-TiAlN and suitable for dry machining and interrupted cuts.

Details of Experimentation

In this investigation, the cutting variables shown in Table 1 are chosen on the idea of pilot experiments, accessible writing and tool maker's catalogue. In present work, experiments are planned by using CCRD. CCRD has indicated awesome potential to focus on the solidness district of the outline around a main issue controlled by its properties of rotatability and symmetry. Table 1 represent Coded levels of parameters.

Table 1. CCRD Coded levels.

CCRD coded levels	Factors		
	Cutting Speed V, (m/min)	Feed f, (mm/rev)	Depth of cut d, (mm)
-1.682	60	0.1	0.1
-1	90	0.2	0.2
0	120	0.3	0.3
1	150	0.4	0.4
1.682	180	0.5	0.5

The CCRD suggest twenty experimental sets which incorporates eight factorials, six axial and six same centre points set. Design Expert software is used to develop the experimental matrix. Machining response variables are studied by means of second order polynomial regression model [24],

$$Y = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k} a_{ii} x_i^2 + \sum_{i<j}^{k} a_{ij} x_i x_j \tag{1}$$

where, Y is the expected response, x_i and x_j are process variables, a_0 is constant, a_{ij}, a_{ii}, and a_i signify second-order, quadratic and linear terms respectively.

The longitudinal turning tests are conducted on a rigid and high precision CNC lathe machine (Model: SimpleTurn-5076). The machine is provided with spindle power 7.5 kW and speed of 2000 rpm. During machining test, accelerations in tangential, radial and feed directions are recorded using piezoelectric transducer (B&K-4535-B001). The transducer signals are taken on personal computer via Bruel and Kjaer FFT analyzer. The software PHOTON-RT-Pro is used to analysis the vibration data. The roughness of newly developed surface is determined using instrument (Make-Taylor Hobson's Surtronic tester). Digital microscope (Dino-Lite) is utilized for the estimation of flank wear. Interrupted dry machining is performed using a fresh edge until the tool wear reaches 0.2 mm the event of the disastrous failure. The test setup is presented in Figure 1.

Figure 1. Experimental setup.

RESULT AND DISCUSSION

The recommended 20 sets of experiments are conducted and output parameter such as tool wear and tool acceleration are presented in Table 2. An analysis of variance (ANOVA) is reported to identify in order to study statistical significance in the measured cutting parameters, tool wear and acceleration response.

Table 2. Cutting parameters and results.

Run	Actual value			Response variables			
	V (m/min)	f (mm/rev)	d (mm)	V_b (mm)	V_x (mm/s^2)	V_y (mm/s^2)	V_z (mm/s^2)
1	150	0.2	0.2	0.18	0.05356	0.00679	0.00586
2	150	0.4	0.2	0.2	0.01651	0.07990	0.05020
3	180	0.3	0.3	0.17	0.00640	0.00630	0.00692
4	120	0.3	0.3	0.18	0.08242	0.07320	0.08218
5	120	0.3	0.5	0.15	0.04520	0.06330	0.04340
6	90	0.4	0.4	0.17	0.00500	0.05290	0.00800
7	120	0.1	0.3	0.16	0.04234	0.02410	0.03432
8	120	0.3	0.3	0.19	0.09242	0.08310	0.08360
9	120	0.3	0.3	0.19	0.07242	0.08130	0.08270
10	120	0.5	0.3	0.17	0.00840	0.08334	0.00530
11	90	0.2	0.4	0.17	0.02320	0.04410	0.06190
12	120	0.3	0.1	0.19	0.03446	0.03490	0.03952
13	90	0.2	0.2	0.19	0.01183	0.03124	0.04524
14	60	0.3	0.3	0.2	0.00031	0.00040	0.00045
15	90	0.4	0.2	0.18	0.00936	0.00979	0.01084
16	120	0.3	0.3	0.2	0.07342	0.07390	0.07930
17	150	0.4	0.4	0.19	0.01865	0.08227	0.02321
18	150	0.2	0.4	0.13	0.02650	0.02640	0.03749
19	120	0.3	0.3	0.18	0.06242	0.08340	0.09140
20	120	0.3	0.3	0.18	0.08421	0.08360	0.08440

Analysis of Variance (ANOVA)

The ANOVA provides correlation between parameters by multiple regressions and is that the additional reliable method to judge the superiority of a fitted model. In ANOVA table, the statistical significance of the fitted model is evaluated by p-value and F-value. If the p-value is less than 0.05(or 95% confidence), the corresponding term signifies that the model terms are highly significant. It demonstrates that the terms considered within in the models have a major impact. When p-value is greater than 0.05, the terms considered within the models does not have a considerable impact on responses and such terms are considered as insignificant terms for the model. The responses are analyzed using commercial available software (Design Expert). Table 3-7 illustrate ANOVA results for V_x, V_y, V_z, V_b and R_a.

Table 3 presents ANOVA results for the vibration in feed direction (V_x). It can be observed that quadratic term V^2 have most statistical significance followed by f^2 whereas 'f' found not so much important. The term feed (f) also contribute the influence on V_x. The interaction V×f, V×d and f×d observed to be just insignificant.

Table 3. ANOVA results for V_x.

Source	Sum of Square	Degree of freedom	Mean Square	F-value	p-value	
Model	0.01529	9	0.00170	7.68049	0.0019	significant
V	0.00038	1	0.00038	1.71933	0.2191	
f	0.00111	1	0.00111	5.03189	0.0487	
d	0.00000	1	0.00000	0.00361	0.9532	
V × f	0.00007	1	0.00007	0.33170	0.5774	
V × d	0.00013	1	0.00013	0.57611	0.4654	
f × d	0.00002	1	0.00002	0.10263	0.7553	
V^2	0.01015	1	0.01015	45.87238	0.0001	
f^2	0.00535	1	0.00535	24.18142	0.0006	
d^2	0.00303	1	0.00303	13.68077	0.0041	
Lack of Fit	0.00165	5	0.00033	2.94474	0.1305	not significant
Pure Error	0.00056	5	0.00011			
Total	0.01750	19				

Table 4 illustrates analysis for the vibration in radial direction (V_y), it was observed that f (feed) has the strong statistical relevance followed by 'd' whereas the 'V' was found less significant on the vibration in V_y. The product term V^2 observed highest influence followed by d^2 and f^2. The product term V×f also has significant effect on V_y whereas term V×d and f×d are found to be insignificant.

When considering the vibration of cutting tool in tangential direction (V_z), the result (Table 5) indicates that the product term V^2 observed highest influence followed by f^2 and d^2. Additionally it can be revealed that feed has important influence on V_z. The terms 'V' and 'd' showed negligible influence on V_z. The interactions V×f and f×d are significant, while interaction V×d was observed to be insignificant.

Table 4. ANOVA results for V_y.

Source	Sum of Square	Degree of freedom	Mean Square	F-value	p-value	
Model	0.01767	9	0.00196	29.77182	0.0001	significant
V	0.00030	1	0.00030	4.52981	0.0592	
f	0.00345	1	0.00345	52.25447	0.0001	
d	0.00113	1	0.00113	17.20866	0.0020	
V × f	0.00251	1	0.00251	38.02164	0.0001	
V × d	0.00014	1	0.00014	2.19063	0.1697	
f × d	0.00002	1	0.00002	0.32060	0.5837	
V^2	0.00960	1	0.00960	145.53916	0.0001	
f^2	0.00121	1	0.00121	18.38743	0.0016	
d^2	0.00165	1	0.00165	25.01245	0.0005	
Lack of Fit	0.00054	5	0.00011	4.54635	0.0610	not significant
Pure Error	0.00012	5	0.00002			
Total	0.01833	19				

Table 5. ANOVA results for V_z.

Source	Sum of Square	Degree of freedom	Mean Square	F-value	p-value	
Model	0.02035	9	0.00226	36.06874	0.0001	significant
V	0.00000	1	0.00000	0.00333	0.9551	
f	0.00085	1	0.00085	13.47918	0.0043	
d	0.00004	1	0.00004	0.68554	0.4270	
V × f	0.00175	1	0.00175	27.93333	0.0004	
V × d	0.00001	1	0.00001	0.16800	0.6905	
f × d	0.00076	1	0.00076	12.16675	0.0058	
V^2	0.01182	1	0.01182	188.60649	0.0001	
f^2	0.00773	1	0.00773	123.33104	0.0001	
d^2	0.00370	1	0.00370	58.94891	0.0001	
Lack of Fit	0.00047	5	0.00009	3.11753	0.1188	not significant
Pure Error	0.00015	5	0.00003			
Total	0.02098	19				

Table 6 present ANOVA results for tool wear V_b, revealed that cutting speed has the strongest influenced followed by 'f' and 'd'. The interactions V×f and V×d were found less significant whereas interaction f×d observed to be immaterial. This is in great concurrence with the outcome presented by Suresh et al. It is to be noted that, tool wear is not depend only on cutting parameters, also depends on other factors such as tool grade and geometry, overhang length, workpiece hardness etc [22-23].

Table 6. ANOVA results for V_b.

Source	Sum of Square	Degree of freedom	Mean Square	F-value	p-value	
Model	0.00563	9	0.000626	7.892855	0.0017	significant
V	0.00042	1	0.00042	5.302079	0.0441	
f	0.00038	1	0.00038	4.797419	0.0533	
d	0.00156	1	0.00156	19.68487	0.0013	
V × f	0.001301	1	0.001301	16.40774	0.0023	
V × d	0.000128	1	0.000128	1.61491	0.2326	
f × d	0.000512	1	0.000512	6.459642	0.0293	
V^2	1.17E-06	1	1.17E-06	0.014788	0.9056	
f^2	0.000971	1	0.000971	12.25639	0.0057	
d^2	0.00053	1	0.00053	6.685755	0.0272	
Lack of Fit	0.000488	5	9.76E-05	1.600154	0.3093	not significant
Pure Error	0.000305	5	6.1E-05			
Total	0.006423	19				

From the Table 7, it can be concluded that feed has the highest statistical significance followed by 'V' while parameter'd' was discover less effect on R_a. This shows acceptable concurrence with Auici et al.[3], D'Mello et al.[21] and Boy et al.[25]. The interactions V×f has statistical and physical significance on R_a. The interactions V×d and f×d were found to be less significant. The quadratic terms V^2 and d^2 also have significant interaction with R_a. It is concluded that the estimation of R_a increment as feed and cutting speed increment.

Table 7. ANOVA results for R_a.

Source	Sum of Square	Degree of freedom	Mean Square	F-value	p-value	
Model	8.88663	9	0.98740	25.32339	< 0.0001	significant
V	0.19521	1	0.19521	5.00654	0.0492	
f	2.15253	1	2.15253	55.20474	< 0.0001	
d	0.01601	1	0.01601	0.41073	0.5360	
V × f	4.10211	1	4.10211	105.20451	< 0.0001	
V × d	0.01447	1	0.01447	0.37103	0.5560	
f × d	0.00217	1	0.00217	0.05569	0.8182	
V^2	1.71517	1	1.71517	43.98812	< 0.0001	
f^2	0.06177	1	0.06177	1.58408	0.2368	
d^2	1.14998	1	1.14998	29.49292	0.0003	
Lack of Fit	0.30476	5	0.06095	3.57892	0.0940	not significant
Pure Error	0.08515	5	0.01703			
Total	9.27654	19				

Regression Modeling

The aim of this research to analyze tool acceleration, surface roughness, and tool wear through predictive modeling. The multiple regression method of order two is implemented to develop models for R_a, V_x, V_y, V_z and V_b and are presented in Equations. (2-6)

$$\begin{aligned} R_a &= -0.14919*V - 28.44322*f - 15.34347*d + 0.23869*f*V + 0.014175*d*V \\ &+1.64750*d*f + 0.000290205*V^2 + 4.95641 f^2 + 21.38641*d^2 + 16.87013 \end{aligned} \tag{2}$$

$$\begin{aligned} V_x &= 6.22191E-3*V + 0.861*f + 0.770*d - 1.00954E-003*V*f - 1.33046E \\ &-003*V*d + 0.169*f*d - 2.23224E-5*V^2 - 1.45864*f^2 - 1.09714*d^2 - 0.54072 \end{aligned} \tag{3}$$

$$\begin{aligned} V_y &= 4.00862E-03*V - 0.193*f + 0.691*d + 5.90113E-003*V*f - 1.4164E-3*V*d \\ &+0.1625*d*f - 2.17083E-005*V^2 - 0.69445*f^2 - 0.80995*d^2 - 0.2796 \end{aligned} \tag{4}$$

$$\begin{aligned} V_z &= +4.42197E-003*V + 0.681*f + 1.083*d + 4.93181E-003*V*f - 3.8247E-4*d*V \\ &-0.9765*d*f - 2.40957E-005*V^2 - 1.75364*f^2 - 1.21239*d^2 - 0.43577 \end{aligned} \tag{5}$$

$$\begin{aligned} V_b &= +0.004536*V + 0.3702*f + 0.4345*d + 0.000708*V*f - 0.000375*V*d \\ &-0.062500*d*f - 0.000013*V^2 - 0.422727*f^2 - 0.393977*d^2 - 0.376932 \end{aligned} \tag{6}$$

The correctness of developed model is verified by means of regression coefficient (R^2). The R^2 esteem near to one is alluring and the model represent much reliable. In other words, when R^2 value approaches unity, higher the model fits the experimental data. The R^2 value for R_a, V_x, V_y, V_z, and V_b is found as 0.95, 0.87, 0.96, 0.97, and 0.87 respectively which suggest that the created models are statically noteworthy and can give solid appraisals within the limits of factor considered. The diagnostic checking of models is done with the help of normal residuals plot. Figure 2 show residual plots for R_a and V_x. The plot reveals that the residuals lie on the brink of line which illustrates that error distributed normally and therefore the model does not indicate any inadequacy and provide the reliable prediction.

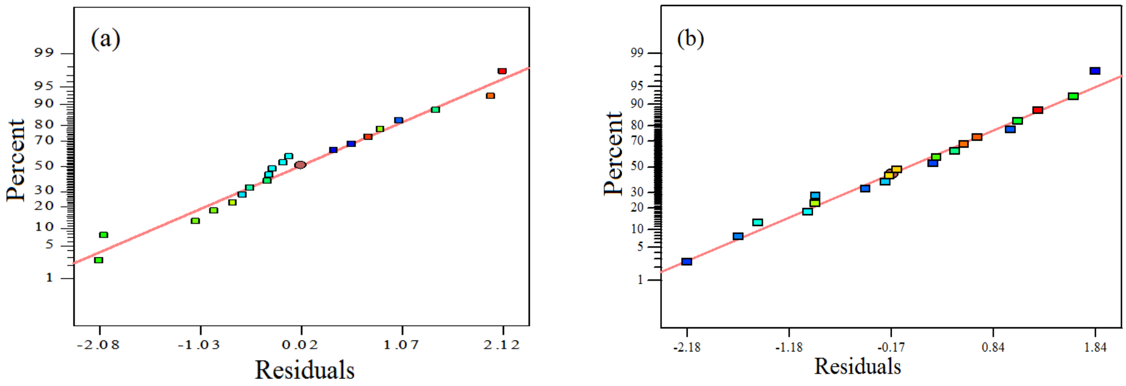

Figure 2. Residuals plot for (a) R_a (b) V_x.

Figure 3 explores residuals analysis for V_x and V_b with respect to twenty cutting conditions. The residuals don't show any undeniable pattern and are appropriated in both positive and negative both sides. This infers the model is sufficient and there is no motivation to associate any infringement.

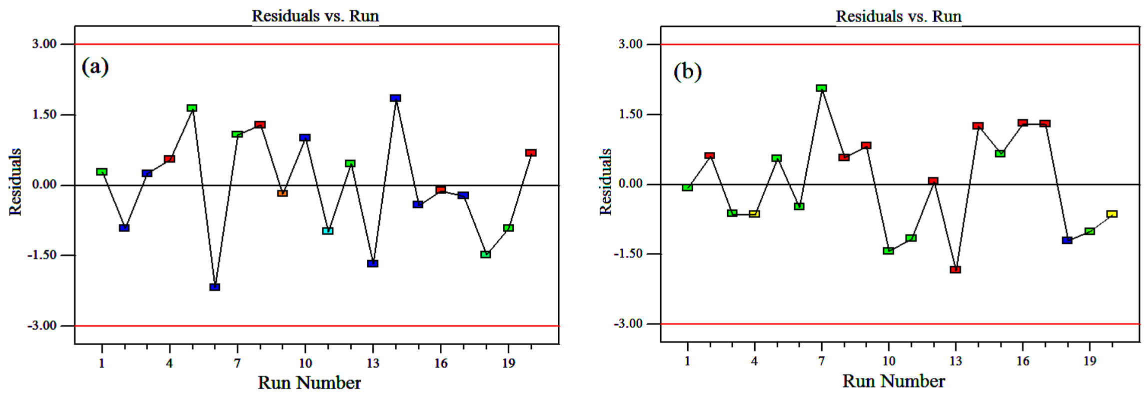

Figure 3. Normal probability of residuals (a) V_x (b) V_b.

In addition to this, optimization is carried out to achieve a better product quality with minimum tool vibration. In the present study, surface roughness, and V_x, V_y and V_z were targeted to the minimum, keeping other variable in range. The optimized tool acceleration is found as, V_x=0.0232 mm/sec^2, V_y=-0.0044 mm/sec^2 and V_z= 0.0167 mm/sec^2. The optimized R_a value is observed 0.7 micrometer and cutting speed 125.68 m/min, f=0.18 mm/rev, and d=0.42 mm. Figure 4 presents bar graph of desirability for selected cutting condition and the responses together with a combined desirability 0.9108.

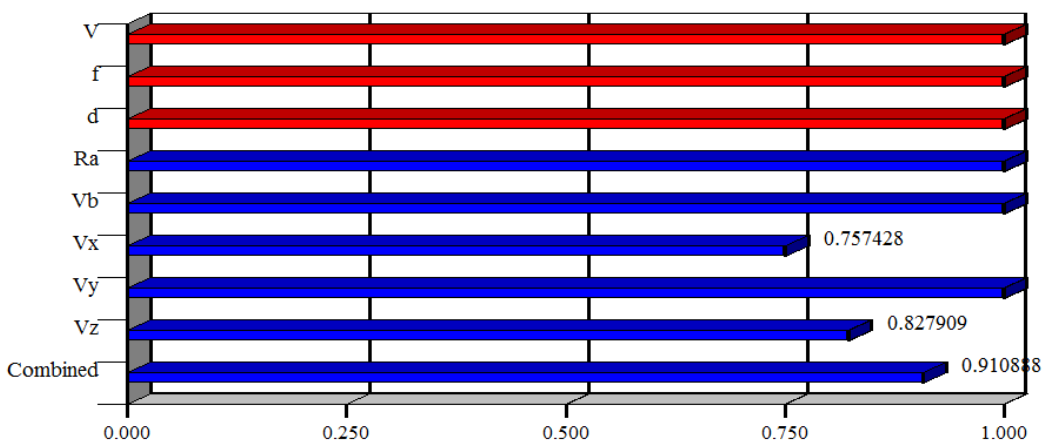

Figure 4. Bar graph of desirability.

Effect on Vibration Signals with Progressive Tool Wear

Figure 5 shows the deviation in acceleration respect to progressive flank wear. It is seen that acceleration signals in all direction is increasing as tool wear increases. Figure 6 shows relationship of flank wear with cutting time. Figure 5-6, signify the distinct wear zone; initial break-down, uniform, and rapid wear. During machining, tool engages with workpiece and tool cutting edge wears out rapidly at the beginning of its use. The acceleration in this stage suddenly increases and which is accurately detected by the accelerometer. Then wear take place at uniform rate. In rapid wear zone, cutting edge wears out faster rate due to higher normal pressure and temperature. This result in plastic flow and catastrophic failure of tool. It is seen that acceleration amplitude responds greatly to catastrophic failure.

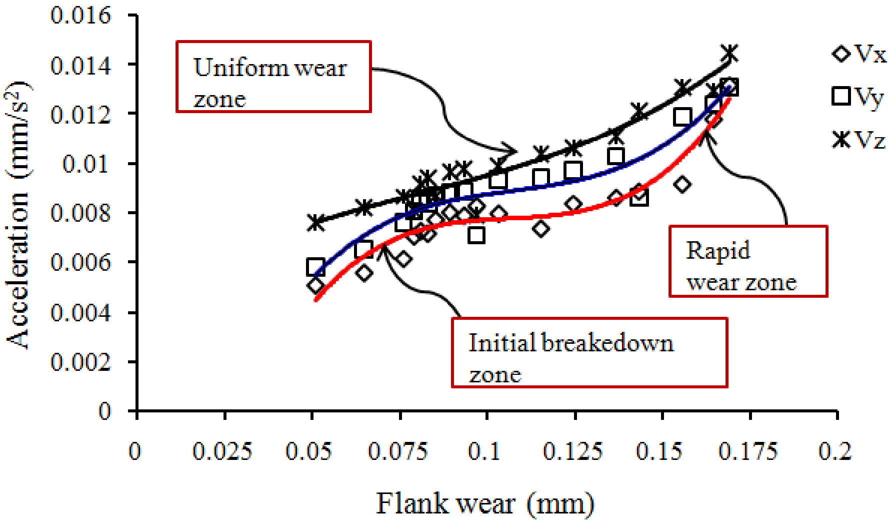

Figure 5. Acceleration Versus Flank wear (V=90m/min, f=0.2mm/rev, d=0.4mm).

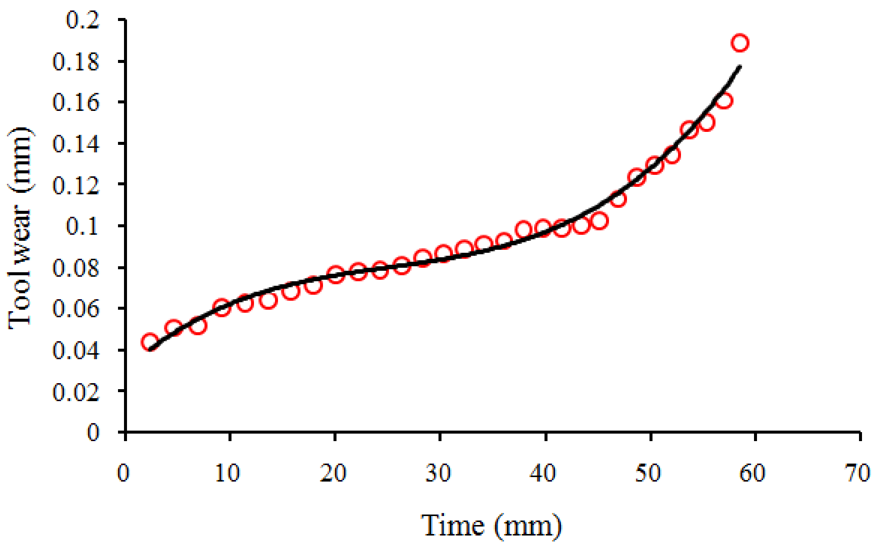

Figure 6. Tool wear Versus Time (V=120m/min, f=0.3mm/rev, d=0.3mm).

From Figure 7(a-c), it very well may be seen that tool vibration signals are random in nature. The higher tool acceleration is seen in tangential direction compare with acceleration in other two directions. The pattern of accelerations is observed in fluctuating in nature in radial, feed and tangential directions. When turning with new cutting edge, the high acceleration peaks are found in lower (up-to 1100 Hz) and higher frequency zone (up-to 15 kHz). In chosen machining parameters, 12 sets out of twenty designed condition, the greatest value of acceleration amplitude is seen in the range of 3 kHz - 10 kHz. Table 8 represent observed frequency range for different cutting condition. For cutting speed 150 m/min, feed 0.4 mm/rev and depth of cut 0.2 mm, a continuous chip formation take place near the location of sensor placed. The chips beating the sensor in every rotation and therefore unexpected increase in acceleration value is observed (see Figure 8).

Table 8. Frequency range for various cutting conditions.

Run	Trial set			Frequency band Hz		
	V	f	d	V_x	V_y	V_z
1	150	0.2	0.2	44-9520	26-10695	65-10750
2	150	0.4	0.2	121-8646	76-11180	96-12810
3	180	0.3	0.3	16-11160	45-11940	16-10880
6	90	0.4	0.4	96-9562	35-14130	11-14260
10	120	0.5	0.3	397-6453	353-6512	107-8342
16	120	0.3	0.3	59-6550	76-6652	172-8970
14	60	0.3	0.3	42-8260	23-8760	32-9320
20	120	0.3	0.3	323-6956	365-6552	101-9012

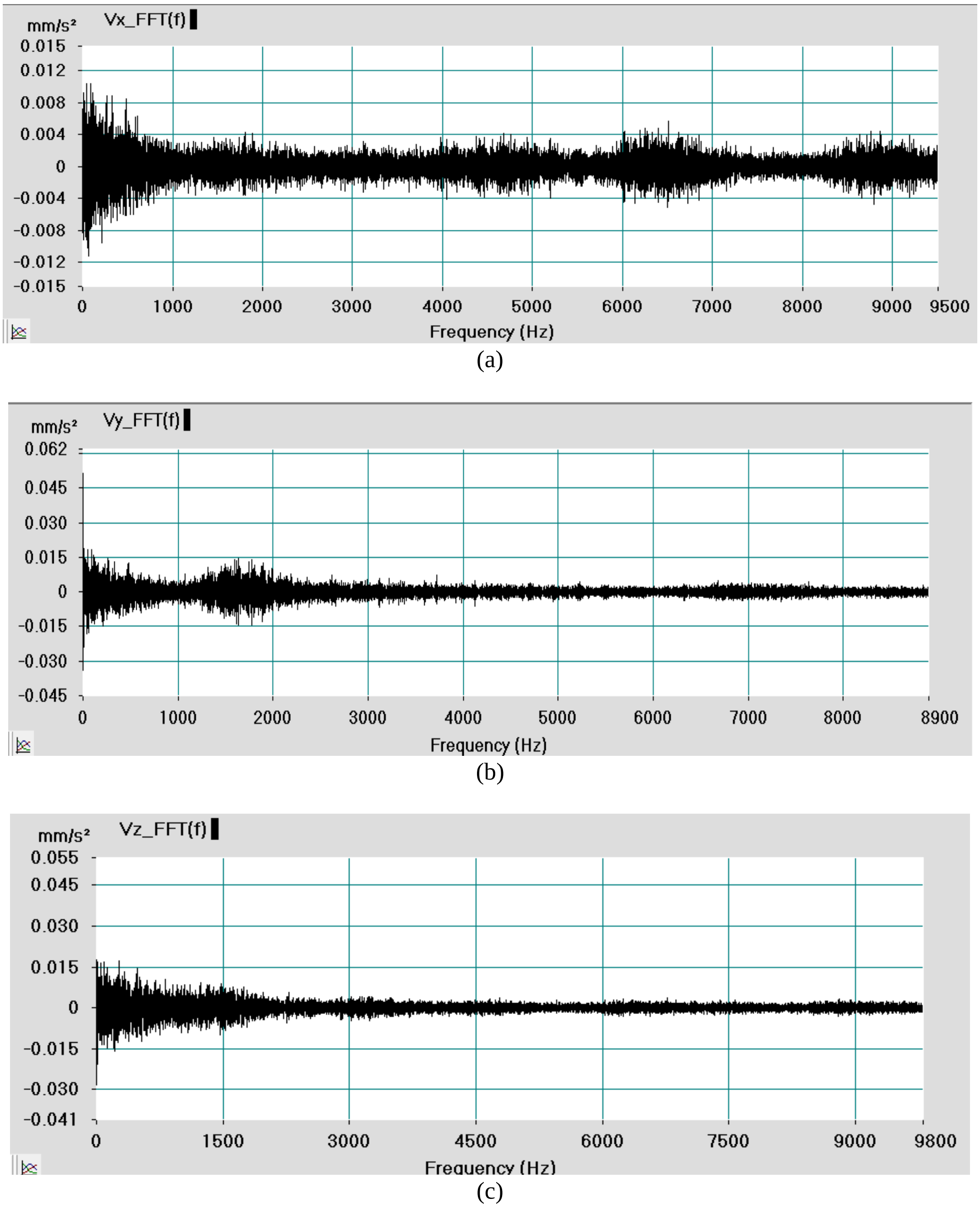

Figure 7. Vibration response at V=90m/min, f=0.4mm/rev, d=0.4mm and V_b=0.078mm (a) V_x (b) V_y (c) V_z.

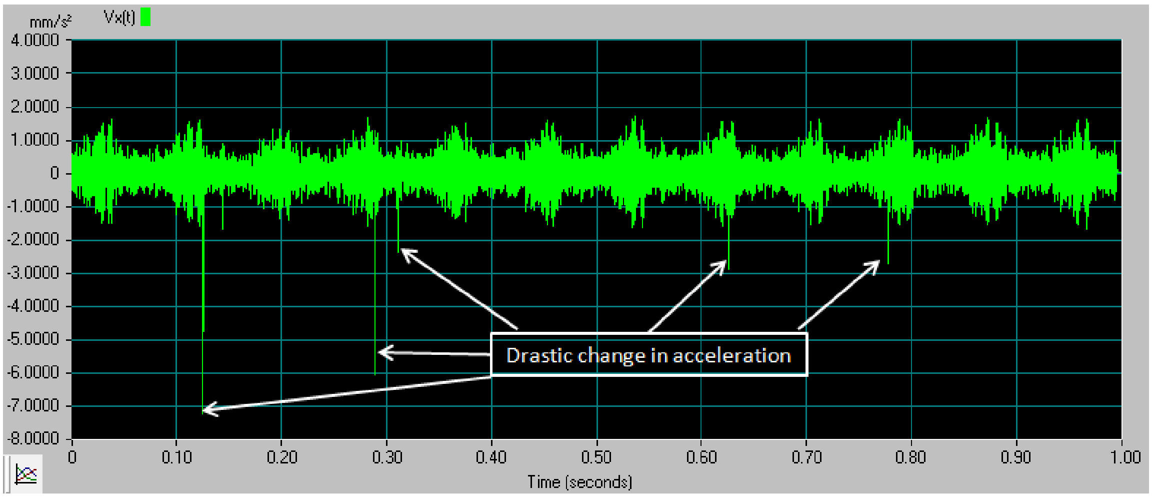

Figure 8. Drastic change in accleration.

Impact of Tool Wear on Surface Roughness

The surface quality of finished part with respect to time is shown in Figure 10. At the beginning of machining process, the surface roughness value decreases with the time. This happens due to sharp edge of tool. Then, gradual improvement in surface finish is seen because of uniform tool wear. It is to be noted that, in hard turning, good surface finish is observed as tool wear progresses up-to certain value. Similar research is reported by D'Mello et al. [21] and Che-Haron et al. [26].

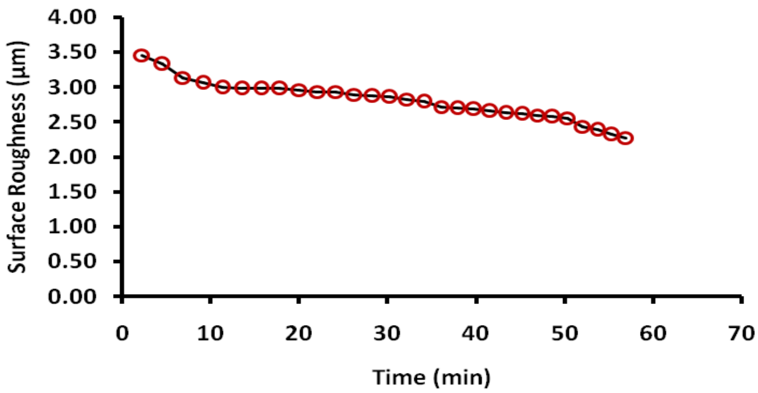

Figure 10. Surface roughness Versus Time (V=120m/min, f=0.3mm/rev, d=0.3mm).

CONCLUSIONS

In the present work, an exploratory examination has been done so as to build up the relationship between cutting parameters, flank wear and surface roughness. Also, ANOVA is presented and some concluding are outlined as follows,

- ANOVA demonstrates that the feed has the highest statistical significance followed by cutting speed though the depth of cut discovered less noteworthy on surface roughness Ra.
- The most noteworthy factual criticalness on vibration in the feed direction (V_x) followed by f^2 (feed) while the profundity depth of cut discovered less impact.
- Analysis for the vibration in a radial direction (V_y) showed that feed has the strong statistical significance followed by the depth of cut while the cutting speed observed less significant on the vibration in Vy.
- When considering the vibration of a cutting tool in a tangential direction (V_z), the term cutting speed (V^2) has the elevated impact followed by term feed (f^2) and depth of cut (d^2). The terms cutting speed and depth of cut showed negligible influence on V_z. On the other hand, the interaction V×f and f×d are significant, while interaction V×d was found to be insignificant.
- Cutting speed has the most grounded on tool wear than feed and depth of cut. When turning hard materials, increased cutting speed increases tool wear drastically due to increase in temperature in a contact zone.
- Tool vibration in tangential direction (V_z) is found higher than the vibrations V_x and V_z.
- The surface roughness value decreases drastically with the time due sharp edges of the cutting tool. Better surface finish is observed as tool wear progresses up-to 0.136mm.

- Vibrations especially measured in radial directions are conspicuously influenced by the depth of cut followed by feed value. However, tool vibrations measured in tangential direction seen to decrease with increase in cutting speed.
- Regression coefficient (R^2) value is discovered near 0.9 which indicate models are appropriate and provides a superb rationalization of the link between cutting parameters and tool vibrations.
- High vibrations are seen in the range of 3 kHz - 16 kHz. The frequency has varying nature for variable cutting parameter. However, unexpected acceleration bigger values are observed when continuous chip formation started.

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