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The Correlation Between Tool Wear and Vibration Signals from Piezoelectric in End Milling of AISI P20+NI

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ABSTRACT

This paper presents, the relationship between the flank wear of a carbide cutting tool and the vibration signal under various cutting conditions during the end milling of AISI P20. AISI P20 steels are typically used for making plastic injection mold, die extrusion, blow molding and various other components. The tests were conducted under various combinations of the cutting speed (200 and 300 m/min) and feed rate (0.1 and 0.2 mm/tooth), whilst the depth of cut is kept constant at 1 mm. The vibrations due to the flank wear were measured using piezoelectric sensors embedded within an integrated rotating dynamometer. The amplitude of the vibrations increased with increasing flank wear. The experimental results showed that the amplitude of the vibration signals increased due to the progression of the flank wear as well as with an increase as the cutting speed..

Keywords*:* *Rotating Dynamometer, Piezoelectric, Vibration Signal, Milling Process*

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Introduction

Machining process is commonly considered as secondary process in manufacturing operations and widely used in the manufacturing industry in the world. According to Yu [1], more than 70% of machining processes are used in the manufacturing industry in the world. Machining process, also known as metal cutting mechanics involves the interaction between the surface of the tool and work piece [2]. The aim of a machining process is to achieve very good quality of the work piece which includes surface finish and specific geometrical dimensions between tolerances. The condition of the cutting tool is an important factor in metal cutting operations as this can result in much higher costs due to waste components, damage to the machine tool, and unscheduled downtime [3]. In the machining process, there are several phenomena occur during the cutting process and can be measured such as cutting force, vibration, acoustic emission, torque, surface finish, sound etc.

Generally, Tool Condition Monitoring (TCM) can be classified into two major categories; direct and indirect methods [4, 5]. The direct methods of wear prediction, such as visual inspection based on surface textures, are not cost effective and reliable as tool wear monitoring systems. The indirect methods involve the generation of a data acquisition signal during the machining process, which is then analysed to estimate the tool wear. Some researchers [6]-[8] have studied the effects of tool wear on the cutting forces, vibrations, surface roughness and dimensional accuracy. Among the process variables, vibration has received a wide popularity in TCM and it supplies the best information about tool condition due to the fast data collection and interpretation ability [9]. Vibration monitoring is mainly used to detect tool condition, surface roughness, dimensional deviations and chatters in cutting operations. The vibrations are produced by cyclic variations in the dynamic components of the cutting forces [10]. According to the [11], the vibration amplitude caused by interaction of a new tool and work piece is small compared to the worn tool.

Yu aimed to find the correlation vibration signals to the tool wear in a metal turning operation [12]. From the results obtained, they suggested that the vibration signals features in time domain were sensitive more to cutting condition, whereas frequency-based features correlated well with the tool wear. They concluded that the vibration signals were effective for use in cutting tool-wear monitoring and wear qualification. Orhan et. al investigated the relationship between the vibration signal and tool wear during the end milling process of AISI D3 cold work tool steel [10]. Time and frequency domain analysis was performed to describe the vibration signal during the test. They concluded that the vibration amplitude increased with the increasing tool wear.

A.K. Ghani et. al presented a study of tool tool life, surface finish and vibration, while turning nodular cast iron using ceramic tool [7]. The tests have been done under various combinations of speed, feed and depth of cut to verify the change in surface finish of the workpiece due to increasing the flank wear. The vibration was measured using two accelerometers attached to the tool holder. They concluded that surface finish of the work part is not influenced by the progression of the flank wear with under different cutting conditions. They also observed that, as the speed and at low depth of cut increased, the vibration amplitudeduring cutting decreases it remains almost constant with the increase of flank wear.

Kalvoda et. al conducted a series of experiments to detect tool wear and tool damage during the milling process [13]. The experiments were carried out by taking a three-axis vibration signal on the *x*, *y* and *z* axis. Vibration signals observed through three accelerometers (CROSSBOW) mounted on the spindle. As the results, the best performance of vibration amplitudes was recorded in the *x*-axis and *z*-axis, while the *y*-axis was less sensitive to TCM.

Piezoelectric sensors have been proved to be a versatile tool in the measurement of signals in machining processes and it is widely used for research and development in the industries. Piezoelectric sensors utilized the piezoelectric effect to measure pressure, acceleration, pressure, force and vibration. Piezoelectric effects occurred when stress is applied to a material and it creates a strain or deformation in the material. In a piezoelectric material, piezoelectric sensor is in a state of mechanical stress and this strain will generate a voltage, which is called as a direct piezoelectric. In another word, piezoelectric effects are the effect in which energy is converted to electrical charge and also in mechanical design and the effects are reversible. With the raw signals generated from sensors, the flank wear width, *VB* can be determined.

This paper investigated the correlation between flank wear and vibration signals using a wireless telemetry system based on inductive coupling as the data transmitter for the end milling of an AISI P20 steel cutting tool using a coated with tungsten carbide. AISI P20 steels are typically used for making plastic injection mold, die extrusion, blow molding and various other components [14]. The steel is supplied in hardness range of about 32–36 HRC [15]. The quenched and tempered mediurn carbon CrMo (P20) steel has been widely used for plastic dies because of its machinability and excellent polishing property [15]. The transducer element used in the integrated rotating dynamometer was based on a cross beam type of piezoelectric sensor. It is capable of measuring three components of vibration signals in the direction of cutting force which is in direction of main cutting force (V_c), thrust force (V_t) and perpendicular cutting force (V_{cN}). The advantage of this rotating dynamometer is its flexibility as it can be assembled with a variety of cutting tool sizes and geometries and it also could be used as the tool condition monitoring systems, optimisations, machine tool design and also dynamics of the cutting process. This paper describes the application of the piezoelectric embedded within an integrated rotating dynamometer for monitoring online cutting tool wear by measuring the vibration signals. The vibration signals were then analysed using a new statistical-based method called the Integrated Kurtosis- based Algorithm for Z-filter Technique (I-Kaz), pioneered by [16].

Experimental Set Up

In this study, the milling process was conducted in dry cutting conditions using a Spinner VC450 CNC machine. This experiment was carried out for the end milling of an AISI P20 steel cutting tool using a coated with tungsten carbide. The cutting conditions are shown in Table 1. The piezoelectric are arranged for detecting the vibrations in three channels simultaneously. Three pieces of piezoelectric sensors were mounted onto the transducer elements, where the maximum values of strain and stress were obtained to achieve the maximum sensitivity and repeatability of the piezoelectric sensors. ANSYS was used to perform the static analysis of the force sensing element that was subjected to three directions of forces. The transducer element was integrated into the rotating dynamometer based on inductive coupling for the detection the tool wear. When the external forces were applied to the transducer elements, the changes in stress and strain occurred on the surface of the material. The piezoelectric converted the stress into voltage, indicating the vibration signals from the force that was exerted.

Table 1: Cutting condition parameters

No. of Exp.	Cutting speed, V_c (m/min)	Feed Rate, f_z (mm/tooth)	Axial Depth of Cut, a_e (mm)	Radial Depth of Cut, a_p (mm)
1	200	0.1	0.4	1
2	200	0.2	0.4	1
3	300	0.1	0.4	1
4	300	0.2	0.4	1

During the milling operation, the insert was periodically removed from the tool holder, and the widths of the flank wear were measured using a microscope. The flank wear data were recorded from the first cutting pass until the flank wear reached 0.3 mm according to the standard recommended value in defining a tool life end-point criterion based on ISO 3685-1993. The vibration signals were collected at a sampling rate of 5 kHz using a wireless telemetry system, and then analysed by the computer using signal analysis based on the I-kaz 3D method, as described by [16].

The experimental set up is shown in Figure 1. The advantage of I-kaz method is the characteristic of signals can be obtained in time and frequency domain and its sensitive to amplitude and frequency changes. Raw signal decomposition makes the frequency range is divided into three fractions are decomposed into three different axis raw signal of axis *x*, *y* and *z*. Time domain signal is split into three frequency range of as showed in Table 2. Based from the decomposition of the signals, the coefficient of I-kaz 3D is obtained by using Equation 1 [16]:

$$Z_3^{\infty} = \frac{1}{N}\sqrt{K_I s_I^4 + K_{II} s_{II}^4 + K_{III} s_{III}^4} \quad (1)$$

Where;
N = number of data
K_I, K_{II} and K_{III} = kurtosis for channel I, II and III
S_I, S_{II} and S_{III} = standard deviation for channel I, II and III

Table 2: Time domain in three frequency ranges

Axis	Frequency Range	Value
x	low frequency range (LF)	0 - 0.25 f_{max}.
y	high frequency range (HF)	0.25 f_{max} -0.5 f_{max}
z	very high frequency range (VF)	0.5 f_{max}

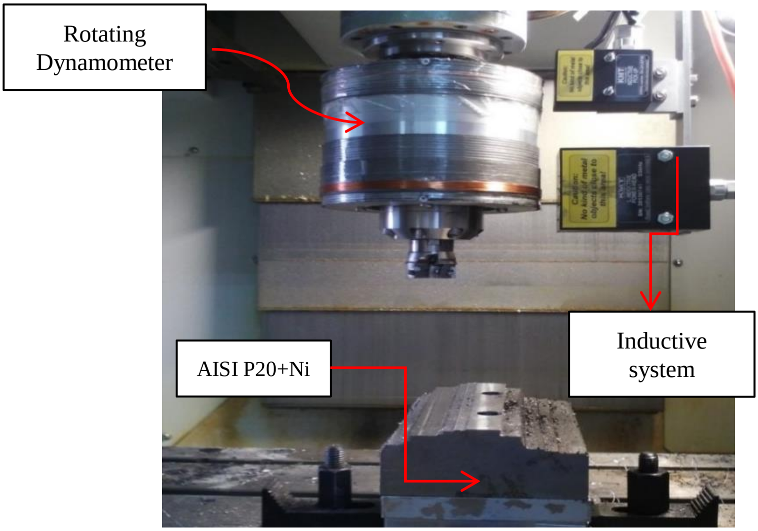


Figure 1: Rotating dynamometer with inductive wireless system

Results And Discussion

Vibration Analysis

Figure 2 shows the plot of dynamic vibration signals in time domain. The gap between the peaks where the tool is not cut or does not touch the workpiece. In time domain results, it is apparent from the graphs that the vibration signals in the direction of main cutting force, V_c is higher, while the vibration signals in the direction of thrust force, V_t is lower than V_c and V_{cN}. This is caused by the contact zone of the tool on the direction of thrust and perpendicular cutting forces are small due to the end milling process [19]. The amplitude of the vibration signals increase with an increase in the flank wear, *VB* until the criterion of *VB* = 0.3 mm was reached, see Figure 3. From this figure, it can be seen that the tool wear causes increasing the vibration amplitudes for all the three vibration components. This is possibly due to the larger frictional forces on the flank surface when the tool is worn [20]. Besides that, among the three vibration components (V_c, V_t and V_{cN}), the magnitude of V_c component is very dominant for TCM, which gradually decreases for the components of V_t and V_{cN}, and therefore have a minimal response to the change of tool wear.

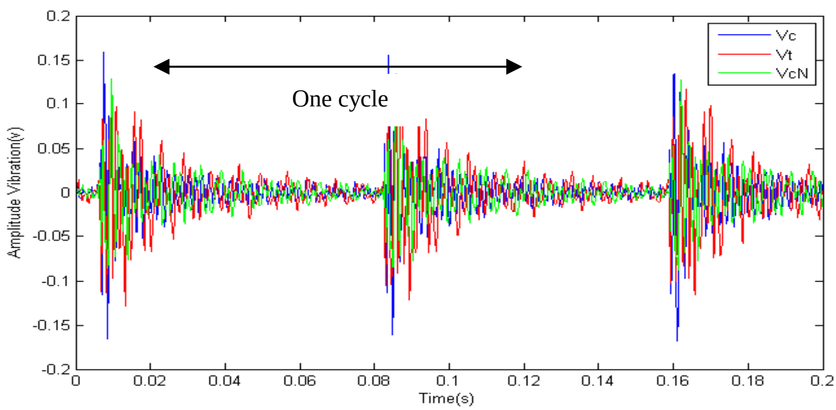
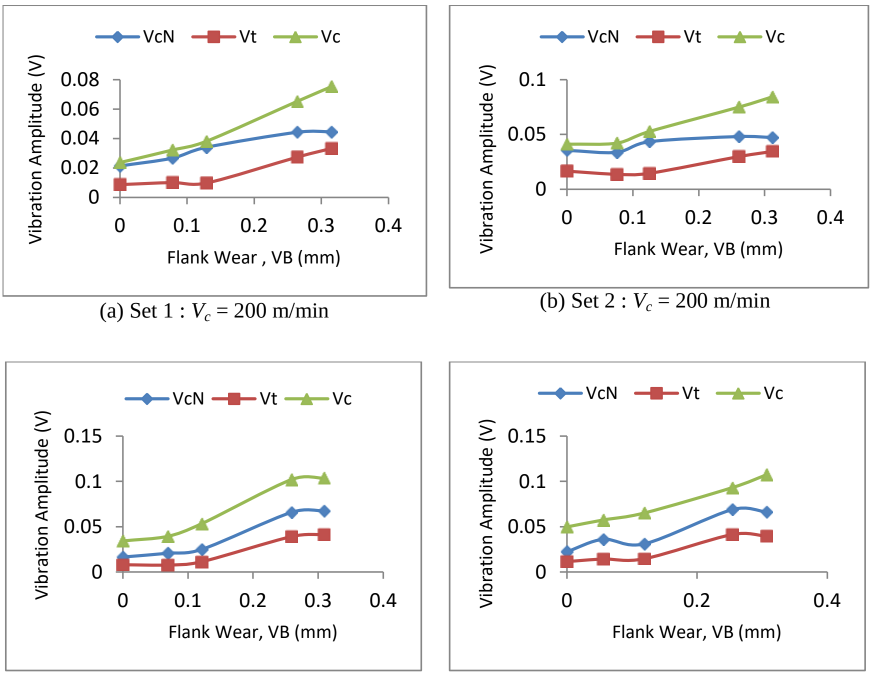


Figure 2: Plots of vibration signals in time domain

The effects of tool wear can be seen clearly seen when the signals are plotted in the frequency domain. According to [10] the vibration generated during the cutting process is caused by the interaction that occurs between the tool and the workpiece which has frequency characteristics of the cutting tool simultaneously, which is 1x, 2x, 3x, and etc. Under the normal cutting conditions, the dominant frequency component is around the frequency of cutting tool (Tool Passing Frequency - *TPF*). TPF can also be determined by using Equation (2):

$$TPF = \frac{n\ X\ NT}{60}\ \text{(Hz)} \qquad (2)$$

Where;
n = spindle rotating speed (rpm)
N_T = teeth number of cutting tool



(a) Set 1 : V_c = 200 m/min

(b) Set 2 : V_c = 200 m/min

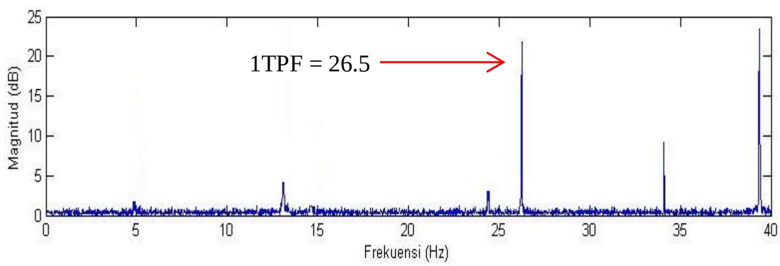
(c) Set 3 : V_c = 300 m/min

(d) Set 4 : V_c = 300 m/min

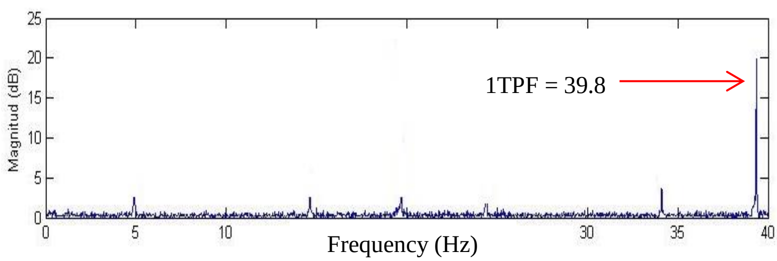
Figure 3: Variation of vibration amplitude with flank wear, *VB*

Figure 5 shows analysis of cutting tool vibration in the frequency domain. From the spectrum plot, the tool passing frequency is around 39.8 Hz. As shown in Figure 5(a), is clear that the frequency of the first cutting tool (1TPF) generated is 26.2 Hz (Vc = 200 m / min). At 300 m/min, the tool passing frequency is also increases to 39.4 Hz, see Figure 5(b). This results are almost similar to the frequency obtained if calculated by using Equation (2).

The resultant vibrations measured for the experiments are shown in Table 2. Generally, as the cutting speed and feed rate increased, the amplitude of the vibration signals increased as well. Table 2 also shown the lowest values of resultant vibration is obtained at 200 m/min cutting speed and 0.1 mm/tooth of feed rate. As the cutting speed increase from 200 m/min to 300 m/min at a constant feed rate of 0.2 mm/tooth, resultant vibration increase by 18%. In addition, by increasing the feed rate, it also affected the amplitude of the vibrations when the cutting speed and depth of cut were kept constant. As shown in Table 2 that as the feed rate is increased from 0.1 mm/tooth to 0.2 mm/tooth at the constant speed of 200 m/min, the resultant vibration also increased by 70% due to the progression of the flank wear at a constant depth of cut. The main reason of this occurrence was due to the increase of chip thickness produced during the cutting operation that consequently resulted in the increase of the tool-chip contact area and cutting forces [21].



Frequency (Hz)



(b) V_c = 300 m/min

Figure 4: Plots of vibration signals in frequency domain

Table 2: Results of vibrations from experiments

No. of Exp.	Cutting speed, V_c (m/min)	Feed Rate, f_z (mm/tooth)	Axial Depth of Cut, a_e (mm)	Resultant Vibration, V_r (V)
1	200	0.1	0.4	0.033
2	200	0.2	0.4	0.056
3	300	0.1	0.4	0.039
4	300	0.2	0.4	0.058

The effect of cutting speed (V_c) and feed rate (f_z) on resultant vibration (V_R) is shown in Figure 4. As shown in Figure 4, low resultant vibration are obtained on the low interaction of cutting speed and feed rate, while the high resultant vibration are obtained on the high interaction of cutting speed and feed rate. From Figure 4, the resultant vibration was increased because of increasing of cutting speed and chip cross-section with feed rate. The increasing of resultant vibration is due to the increase in cutting temperature in the shear zone that consequently results in the reduction of the yield strength of the workpiece material, chip thickness and tool-chip contact length [22]. In such graphs, it can be appreciated that the resultant vibration increases with the simultaneous increase of cutting speed and feed rate while the depth of the cut was kept constant.

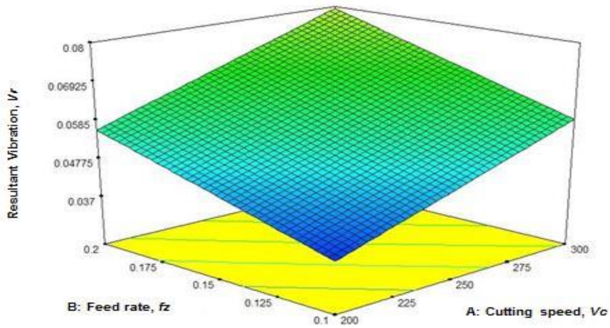


Figure 5: Effect of cutting parameters on resultant vibration

The amplitude of vibration for V_c against flank wear are presented in Figure 6 – 7 for different cutting speed and feed rate, respectively. Figure 6 shows the trend of amplitude of vibration for V_c against flank wear when the cutting speed was manipulated (200 m/min and 300 m/min) at the constant feed rate of 0.1 mm/tooth and depth of cut 0.4 mm. The amplitude of vibration increases with the increasing of speed at a constant feed rate and depth of cut. It's due to the increasing of cip size produced during the cutting process. Therefore, a higher forces required to produce a larger cip size. As the speed increases from 200 to 300 m/min, the amplitude of vibration increases at constant feed rate and depth of cut. While Figure 7 shows the results of the vibration amplitude at two different feed rates of 0.1 and 0.2 mm/tooth and at a constant cutting speed of 200 m/min and axial depth of cut of 0.4 mm. At a higher feed rate (0.2 mm/tooth), the amplitude of vibration was found to be slightly larger than at feed rate of 0.1 mm/tooth due to the progression of flank wear.

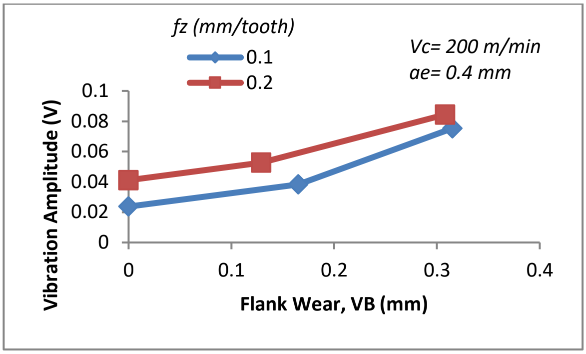


Figure 6: The amplitude of vibration for different cutting speed

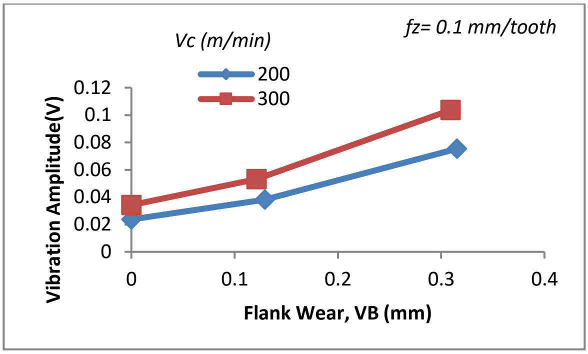


Figure 7: The amplitude of vibration for different feed rate

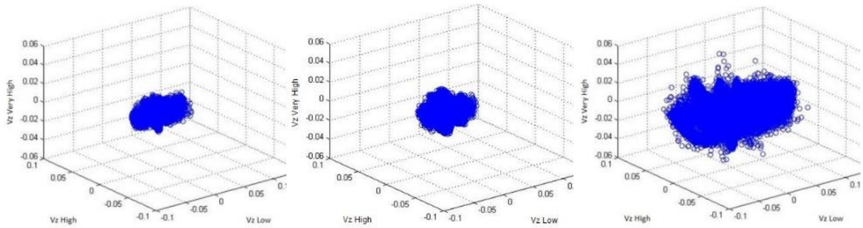
I-Kaz 3D Analysis

The I-kaz 3D analysis of the vibration signals for the sharp tool (VB < 0.1 mm), medium worn tool (0.1 < VB < 0.3 mm) and worn tool (VB > 0.3 mm) are shown in Figure 8. Prior to plotting in three axis representations, the signals are decomposed into three frequency ranges. As can be seen in Figure 8, it can be observed that the changes of data scattering are highly significant due to the progression of flank wear. Visually the results show that the space of scattering in amplitude of the vibration increases due to progression of flank wear during the milling process. It can be seen from the Figure 8 that the data scattering is small and short during the sharp tool. But when the flank wear, VB > 0.3 mm (worn tool), the data scattering becomes larger and elongated compared to the data obtained with the sharp tool and medium worn tool.

The value of I-kaz coefficient, Z^∞ is important because it indicates the correlation between the vibration signals and the tool wear progression.

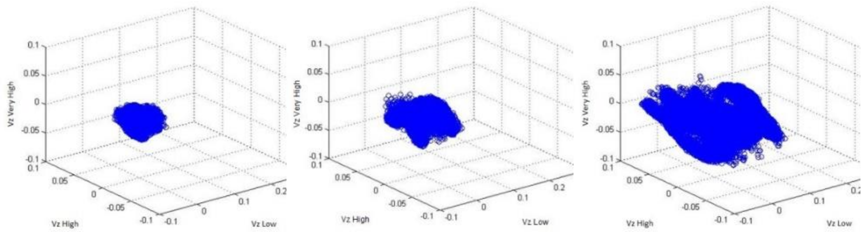
i Sharp tool (*VB* < 0.1 mm)	**ii Middle worn tool (0.1 < *VB* < 0.3 mm)**	**iii Worn tool (*VB* > 0.3 mm)**

Set 1 : V_c = 200 m/min



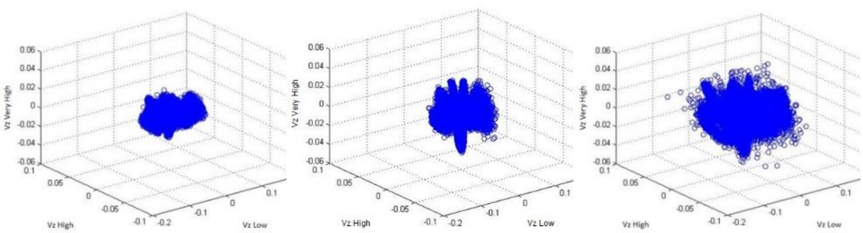
(a) (b) (c)

Set 2 : V_c = 200 m/min



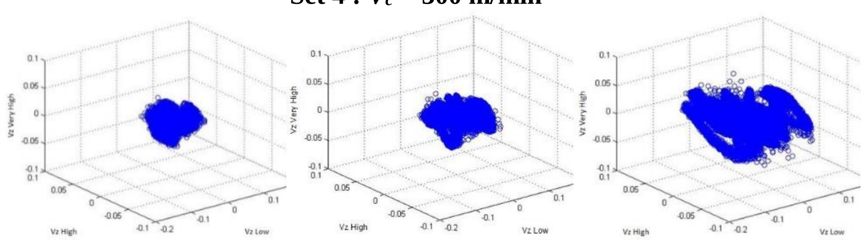
(d) (e) (f)

Set 3 : V_c = 300 m/min



(i) (j) (k)

Set 4 : V_c = 300 m/min



(l) (m) (n)

Figure 8: I-kaz 3D display of graphical representations for cutting force during turning process from the sharp tool until worn tool

The effect of flank wear progression can also be seen by changes of I-kaz coefficient as shown in Table 3. From Table 3, the value of I-kaz coefficient increases due to the increasing of flank wear width. The increasing of the I-kaz coefficient is due to the widening of the contact of surface area between the work piece and the tool and then caused the increasing of resistance to the movement of the tool on the work piece surface area. Therefore, the amplitude of vibration increased and resulted in bigger value of I-kaz coefficient. This was similar to what had been stated in previous studies, whereby a larger I-kaz coefficient value indicates a higher degree of data scattering and vice versa [18].

Table 3: Correlation of tool weal and I-kaz coefficient

No. of Exp.	Z^{∞} **Sharp tool (VB < 0.1 mm)**	Z^{∞} **Middle worn tool (0.1 < VB < 0.3 mm)**	Z^{∞} **Worn tool (VB > 0.3 mm)**
1	4.21 E -10	4.61E-10	1.95 E -09
2	5.45 E -10	1.24E-09	5.51 E -09
3	2.47 E -10	4.62E-10	1.75 E -09
4	2.68 E -09	3.23E-09	1.14 E -08

The correlation between I-kaz coefficient and tool wear progression is also shown in Figure 9. It can be seen that the increasing in flank wear value causes the I-kaz coefficient values to increase. Besides that, the value of I-kaz coefficient become higher and the graph curves move upward from sharp tool until tool is worn for all sets of experiments. Furthermore, the value of I-kaz coefficient became higher with an increase in the cutting speed or feed rate at a constant depth of cut.

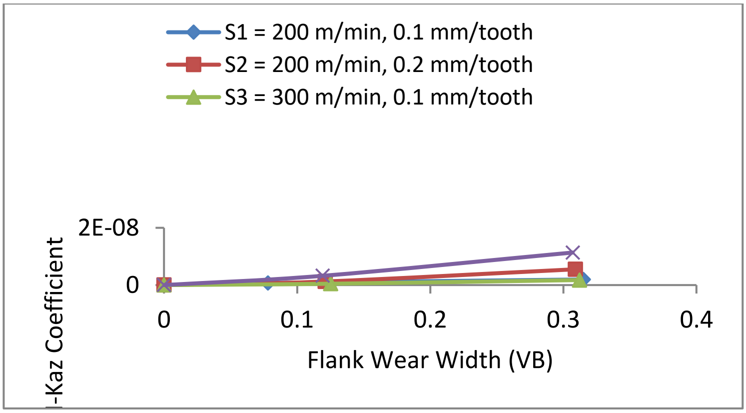


Figure 9: Graph of I-kaz coefficient, Z^{∞} against flank wear width

Conclusion

From the experimental results, following conclusions can be drawn:

1. The magnitude of vibration is very dominant in the direction of V_c than that in the V_t and V_{cN} direction for TCM.
2. The vibration amplitude during cutting process increases as the cutting speed and feed rate increase with the progression of tool wear.
3. The value of I-kaz coefficient increases due to the increasing of flank wear width.
4. A wireless system using embedded sensors within the rotating tool in the milling process can efficiently detect changes of the tool wear.

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