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Vibration–Based online Tool Wear Monitoring Using Piezo Film Sensor Analyzed by I-kaz Multilevel Signal Feature

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Abstract*: Wear in cutting tool is a normal phenomenon in machining process. Problems such as dimensional precision, surface finish quality and defect cost is due to the wear. The wear also can cause unexpected stop time and lower down the manufacturing productivity. Therefore, a system to monitor the progression of the tool wear is needed to predict the wear status and stop machining operation once the wear reach the allowed limit. In this study, the monitoring system was designed by utilizing 2 units of piezoelectric film sensors which are capable of detecting and analyzing signals related to tool holder vibration during the machining process in both feed and tangential axes. The sensors were stacked on x axis and z axis surfaces of the tool holder and signals were channeled to a charge amplifier and then to the digital data acquisition equipment which then display the vibration signal in time domain on the computer screen. A total of 8 experiments were carried out using CNC turning machine. Vibration signal and wear measurement were recorded for each run in the experiment. The experiment were stopped once the wear reach approximately 0.3mm. I-kaz multilevel signal features were extracted from the vibration signal recorded and then correlated with the flank wear status. There is a solid or substantial correlation between the cutting tool wear condition and I-kaz multilevel coefficient value, with average of 0.87 for I-kaz x coefficient (tangential direction) and 0.910 for I-kaz z coefficient (feed direction). This affirm that I-kaz multilevel signal feature can be assigned as the input criterion for the tool condition monitoring system that can estimate the current status of the flank wear on the cutting tools which can prevent defect in the machining process.

***Index Terms*: Tool condition monitoring system, piezo electric film, wear prediction, I-kaz, and correlation.**

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I. INTRODUCTION

Tool condition monitoring system (TCM) is important in machining to increase the availability of machines, to increase productivity, to reduce costs for tooling and to enhance the machined part's quality. The main objective of TCM implementation is to know the current status of cutting insert during machining [1]. The wear monitoring system for the cutting insert is able to warn the machinist on the cutting insert's current condition, therefore the undesirable workpiece conditions and machine tool downtime can be avoided [2]. Tool condition monitoring in machining process can warn the machinist on the severity of the flank wear which can cause deterioration of workpiece dimension and surface integrity [3]. This wear could also contributes to secondary costs. In today's automated manufacturing environment, the development and implementation of real time tool wear monitoring systems are becoming more important [4]. TCM can be applied in two methods, which are direct or indirect. The use of various sensors such as vision system, electrical resistance, optical sensors, and radioactive to directly measure the tool wear is considered under the direct method, which on the other hand is difficult to implement in the real application. Measuring the wear condition under direct method is difficult due to the fact that the tool and the workpiece are still in the continuous contact between them. Moreover, wet cutting machining conditions is also not recommended for this method. Indirect method uses various type of signals from the sensors used or installed such as temperature, vibrations, cutting forces, acoustic emission, current in electric motor, sound and other measurable elements [5]. In indirect method, common signal feature (SF) such as standard deviation, kurtosis, variance, maximum amplitude, average, I-kaz^{TM} and etc. will be derived from the signals captured. These SFs will then be correlated to the wear status. These methods are easier to be applied or implemented as compared to the direct method and are more suitable for the real machining process application.

In the cutting tool wear monitoring application, vibration signals are analyzed in the time domain and frequency domain [6, 7]. Vibration signals can be detected using piezoelectric accelerometer sensor. This sensor is very good to be used in a robust machining condition, such as protection against splashes, moisture, resistance to other objects and debris [8, 9]. However, vibration can also be measured using piezoelectric films in the unit of millimeter or micrometer [10-11].

The small and flexible film size makes it easy to attach to a limited or small area such as a tool holder during machining process. The piezoelectric film location must be as close as possible to the area where the cutting tools meets the

Work piece. This is because the vibration signal quality depends on the location of the sensor and does not depend on the source of vibration [12, 13].In this study, the wear monitoring system was implemented under indirect method and the vibration signals were captured during the machining process.

The signals were captured using two units of piezoelectric film sensors to sense the vibration in tangential and feed direction. The turning machine used was HAAS-10 CNC and the machining process were conducted in a dry condition. A new SF called Integrated Multilevel Kurtosis based Algorithm for Z-Notch Filter or I-kaz multilevel was used to evaluate the vibration signals captured during the machining.

II. METHODOLOGY

In the present study, two phases of tasks involved; phase 1 is the data collection from vibration signals during machining, and phase 2 is the data analysis for I-kaz multilevel signal feature (SF) extraction. Fig. 1 shows the set up for the experiment and the flow of the SF calculation, correlation and finally the prediction.

Experimental Set up and Procedure

The initial step in this experiment is to develop the sensor system and the design of experiment for the turning machining process. Three factors with two levels of parameters were considered in this study. The factors and levels are as follows, cutting speed at 100 and 130 m/min, depth of cut at 0.45 and 0.6 mm and feed rate at 0.12 and 0.16 mm/rev. The turning machining process was carried out in a dry condition using HASS-10 CNC machine. The full factorial machining processes are summarized in Table 1. For the set 1 until set 8 of the experiments, the flank wear (*VB*) progression of each run which involved 50 mm of cutting in horizontal direction will be recorded using microscope Moticom 2.0. Once the *VB* value reached approximately 0.3 mm, the turning operation will be stopped.

Table. 1 Full Factorial Experiment Procedure for Machining Experiment

Exp. No.	Cutting speed, *Vc* (m/min)	Depth of cut, D_c (mm)	Feed rate, *Fr* (mm/rev)
1	100	0.45	0.12
2	100	0.45	0.16
3	100	0.60	0.12
4	100	0.60	0.16
5	130	0.45	0.12
6	130	0.45	0.16
7	130	0.60	0.12
8	130	0.60	0.16

Work piece and Cutting Insert

The material of the workpiece and the cutting insert used in this study were AISI H13 steel and DNMG150604 grade TH1000 (ISO H grade) respectively. The workpiece length and diameter was 120 mm and 85 mm respectively. The cutting insert was a coated carbide type with 0.4 mm nose radius, 6 mm thickness and 15 mm width. The chemical composition and mechanical properties of AISI H13 steel are shown in Table 2 and Table 3.

Table. 2 Chemical Composition of Steel AISI H13 [14]

Chemical composition (%)					
C	Si	Mn	Cr	Mo	V
0.32 – 0.42	0.80 – 1.20	≤ 0.50	4.50 – 5.50	1.00 – 1.50	0.80 - 1.20

Table. 3 Mechanical Properties of Die Steel AISI H13 [14]

Properties	Value
Poisson's Ratio	0.28
Young's Modulus (GPa)	211
Density (kg/m3)	7800
Thermal conductivity (W/m-K)	37
Specific heat (J/kg K)	560
Hardness (HV)	544

Piezoelectric Film Sensors

Two piezoelectric films sensors were stacked on the tool holder's surfaces to sense vibration on the tool holder in cutting and feed directions, as illustrated in Fig. 2. The installation of piezoelectric film sensor in radial or thrust direction is not possible due to space and geometrical limitation.

Fig. 2 shows the piezoelectric film sensors (a) and (b) used for vibration measurement on the tool holder in the tangential (*Vx*) and feed directions (*Vz*) respectively. Piezoelectric films sensors were located near to the tool clamp since the highest vibration effect occur at nearest surface to the tool clamp. In this study, as recommended by Ghani et al. [15], the distance between the piezoelectric film sensors and the tool was 45 mm.

The piezoelectric film type or model used was Measurement Specialist DT1-028K. The specification of piezoelectric film used is stated in Fig. 3 and Table 4.

Table. 4 Specification of piezoelectric Measurement

Item	Dimension
A (Film)	9 mm
B (Electrod)	6 mm
C (Film)	19 mm
D (Electrod)	14 mm
T (Thickness)	40 µmm
Capacitance	1.4 nF

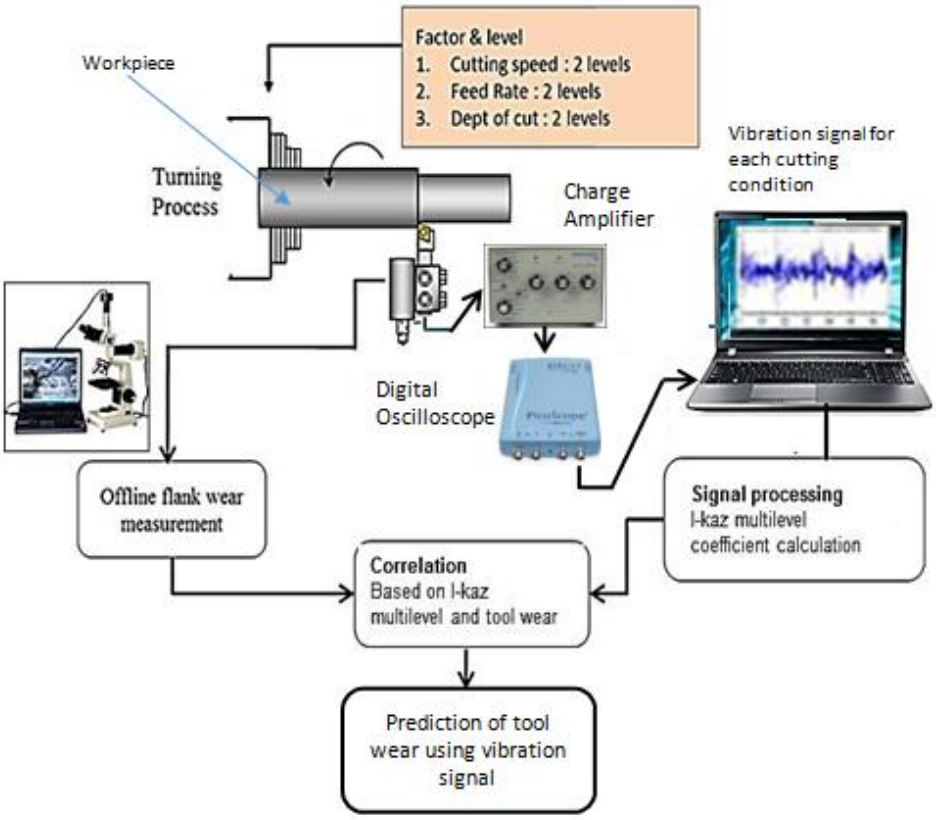

Fig. 1 Experimental set up for the TCM

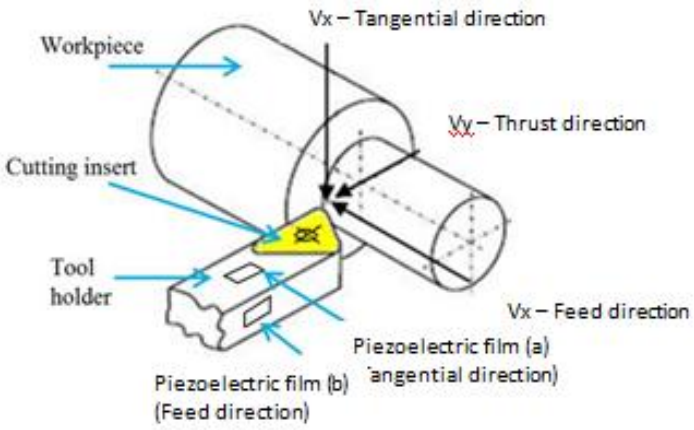

Fig. 2 Piezoelectric film sensors location and direction on the tool holder

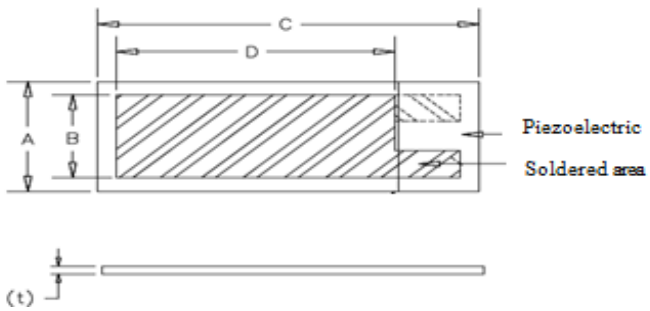

Fig. 3 Piezoelektric film model Measurement Specialist DT1-028K (Measurement Specialist Engineering Inc. 2013) [16]

I-kaz Multilevel SF

The symbol for I-kaz multilevel SF is ${}^{L}Z^{\infty}$. Letter L represents the order number of signal separation in frequency domain. I-kaz multilevel coefficient (${}^{L}Z^{\infty}$) was developed based on the original I-kaz^{TM} (Z^{∞}) SF which was established by M.Z. Nuawi et al. [17]. In any frequency spectrum, the I-kaz^{TM} (Z^{∞}) SF sensitivity on the amplitude and frequency variation can be optimized by separating the original signals into more frequency bands. The Daubechies theorem was applied in this signal separation method in which the origina signal will be divided into L number of frequency bands. This signal separation method was illustrated and summarized in Fig. 4.

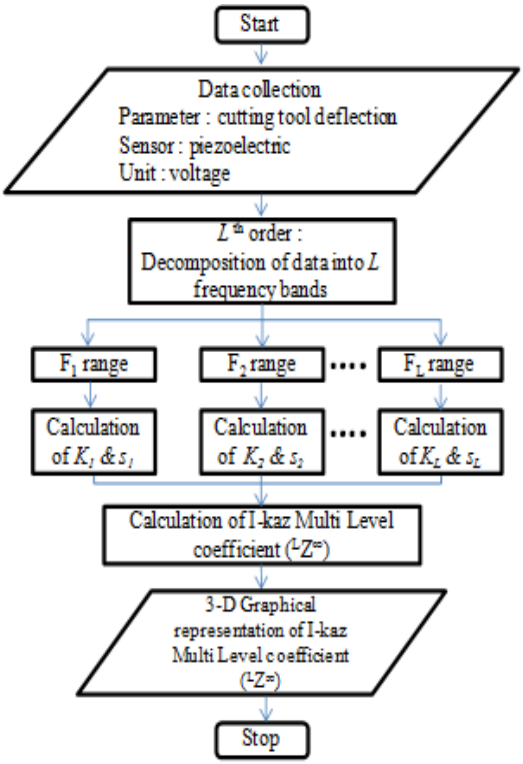

Fig. 4 I-kaz multilevel coeffificnt and signal separation method

The frequency ranges of F_1, F_2, F_3 to F_L in Fig. 1 are calculated based on the number of signal separation, L, and the sampling frequency, f_{max}, set up during the signal acquisition or signal caturing process. Frequency ranges for I-kaz multilevel SF with L^{th} order of signal separation (for i = 1, 2, 3...L) are summarized in equation 1,2 and 3. [18]**:**

$$[F_{i=1\,min} = 0] \leq F_{i=1} \leq [F_{i=1\,max} = f_{max} / (2^{L-1})] \quad (1)$$

$$[F_{i=2\,min} = F_{i=1\,max}] \leq F_{i=2} \leq [F_{i=2\,max} = f_{max} / (2^{L-2})] \quad (2)$$

$$[F_{i=L\,min} = F_{i=L-1\,max}] \leq F_{i=L} \leq [F_{i=L\,max} = f_{max} / (2^{L-i})] \quad (3)$$

The I-kaz multilevel SF value can be determined as in equation 4 [18]:

$${}^{L}Z^{\infty} = \frac{1}{n}\sqrt{K_1 s_1^{\,4} + K_2 s_2^{\,4} + K_3 s_3^{\,4} \ldots + K_L s_L^{\,4}} \quad (4)$$

In which, L is the the order or number of signal separation. In a separate study, I-kaz multilevel coefficient at level 7 of signal separation was found to be most accurate SFs to correlate the wear rate of connecting rod bearing [17, 18].

The standard deviation (s) in Eq. 4 can be computed using Eq. 5 [17]:

$$s = \left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{\frac{1}{2}} \quad (5)$$

The value of Kurtosis K, in Eq. 4 for descrete data sets is defined as in Eq. 6:

$$K = \frac{1}{ns^4}\sum_{i=1}^{n}(x_i - \bar{x})^4 \quad (6)$$

Where, x_i is the data point, $\bar{x}$ is the data mean and s is the standard deviation value.

III. RESULTS AND DISCUSSION

Machining results

For every set of experiment, two types of data were recorded; the flank wear width on the cutting tool and the vibration signals, measured using microscope and captured by the piezoelectric film sensors respectively. The machining process for each experiment set was continued until the flank wear progression measurement reach approximately 0.3mm. Fig. 5, 6, 7 and 8 are the result of the flank wear evolution for AISI H13 steel in CNC turning machining under dry condition. In these figures, the flank wear progression increases as the machining time increase. A polynomial regression plot is best to correlate the relationship between the flank wear measurements versus time.

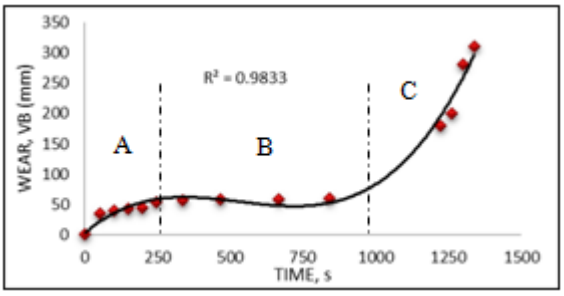

Fig. 5 Experiment 3 - flank wear versus time

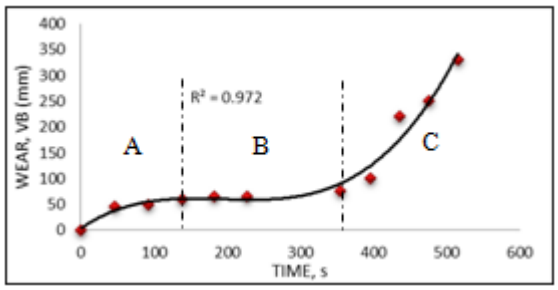

Fig. 6 Experiment 4 - flank wear versus time

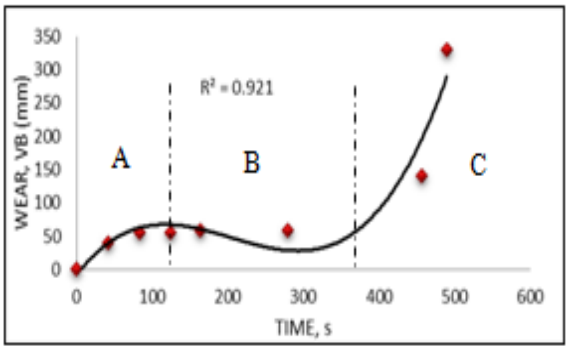

Fig. 7 Experiment 5 - flank wear versus time

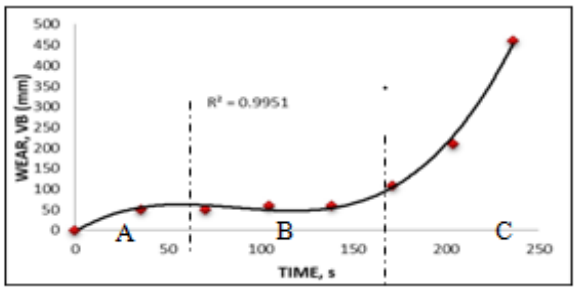

Fig. 8 Experiment 6 - flank wear versus time

The correlation between the flank wear measurement and the machining time in time domain plot as shown in Fig. 5, 6, 7 and 8 can be described under three phases marked with A, B and C region. Region A is referring to flank wear under 65 µm, known as the break-in period, region B is referring to the wear between 65 to 100 µm, known as the steady state and finally region C, referring to wear between 100 to 350 µm and is known as the failure region for.

SF correlation with Wear

The vibration signals on the tool holder were captured by the two piezoelectric films sensors through the digital data acquisition and then recorded in the computer. The vibration signals recorded were in the feed (V_z) and tangential (V_x) directions. The I-kaz multilevel SF for each signal from each machining run has its own values depending on the amplitude of the vibration with respect to the flank wear size. [19]. I-kaz multilevel coefficients ($^{7}Z^{\infty}$) were calculated from the vibration signals in time domain and then correlated to the flank wear status. Fig. 9 and 10 show the sample of vibration signals captured in Experiment 1, Run 3. These figures show the duration, amplitude, start and end of the vibration signals in time domain for each run of machining process. The SFs were calculated in the 10 seconds data window which contain 20 thousands points from the 2000 points/second sampling rate setting on the equipment. The relationship between the flanks wear measurement and the I-kaz multilevel SF values were plotted as in Fig. 11, 12, 13 and 14.

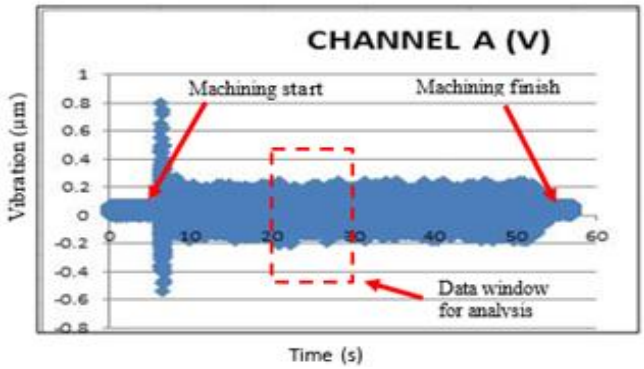

Fig. 9 Vibration Signal in Tangential (Vx) Direction

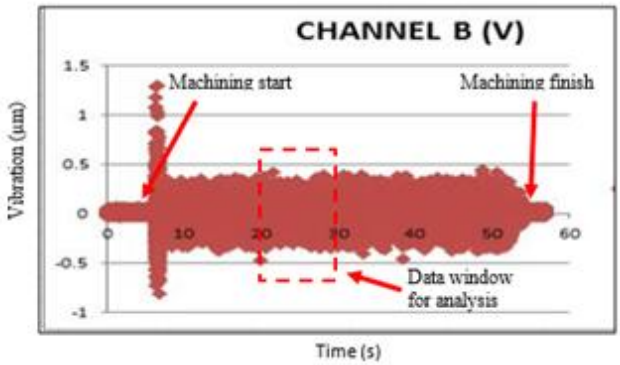

Fig. 10 Vibration Signal in Feed (Vz) Direction

Fig. 11 and 12 show the correlation between I-kaz multilevel SF and the tool's flank wear measurement for experiment 3 in tangential and feed direction. Whereas, Fig. 13 and 14 show the correlation between I-kaz multilevel SF and the tool's flank wear measurement for experiment 5 in tangential and feed direction.

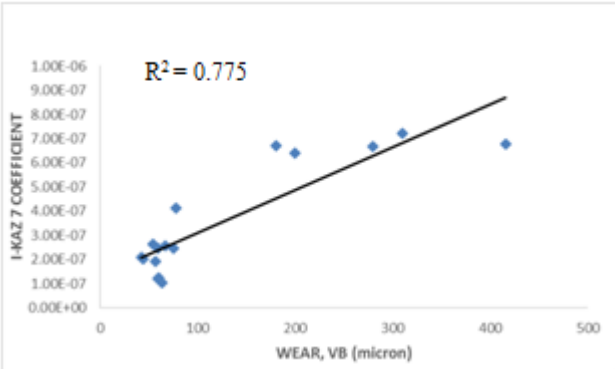

Fig. 11 Experiment 3: I-kaz vs flank wear in tangential direction (Vx)

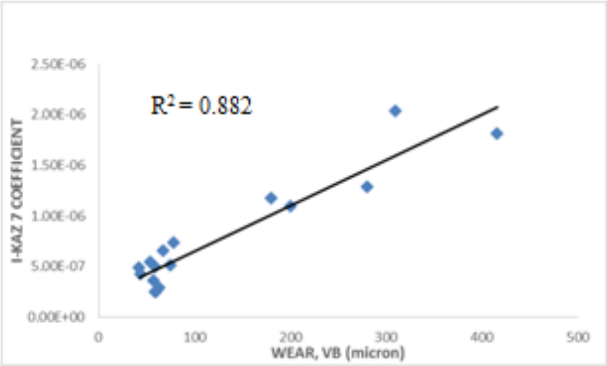

Fig. 12 Experiment 3: I-kaz vs flank wear in feed direction (Vz)

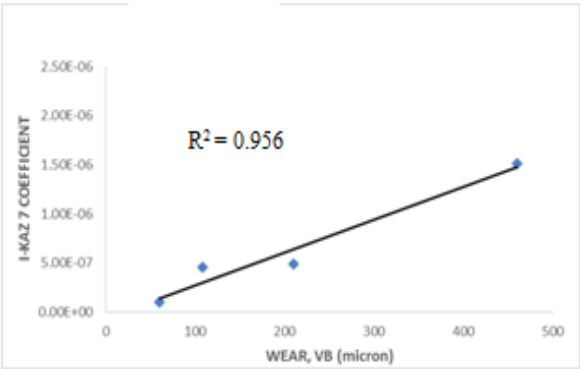

Fig. 13 Experiment 5: I-kaz vs flank wear in tangential direction (Vx)

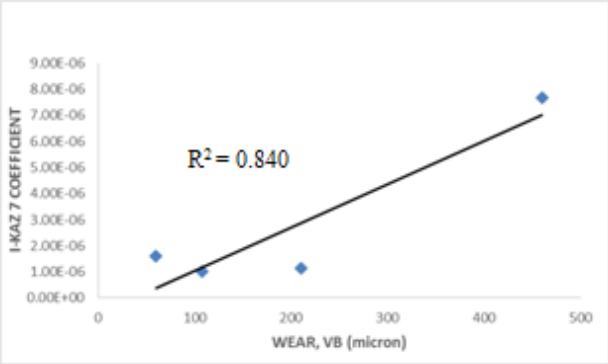

Fig. 14 Experiment 5: I-kaz vs flank wear in feed direction (Vz)

From Fig. 11, 12, 13 and 14, it can be noticed clearly that there is a linear relationship between the ${}^{7}Z^{\infty}$ coefficient and the cutting insert's flank wear. The average correlation (R^2) values between ${}^{7}Z^{\infty}$ coefficients and cutting insert's wear measurements are 0.87 for I-kaz (x) coefficient and 0.86 for I-kaz (z) coefficient. The linear correlation shows that the I-kaz multilevel SF increase as the flank wear increase. A continuous cutting during the machining process will increase the action of shear stress and friction on cutting zone which causing wear on tool also increasing. The increases of tool wear thus affecting higher force and vibration. Since I-kaz multilevel values are directly related to the flank wear measurement, this coefficient values can be applied as the TCM's input parameter for system prediction to predict the flank wear status during machining process.

IV. CONCLUSION

This study discussed on the tool condition monitoring (TCM) by studying the relationship between I-kaz multilevel coefficient values and cutting tool flank wear measurement. The machining experiment were executed on AISI H13 steel as the workpiece using CNC turning machine in dry machining condition with 8 set of machining parameters. Two units of piezoelectric film sensors were fixed on the tool holder surface to detect vibration in tangential and feed direction. The correlation between tool flank wear and ${}^{7}Z^{\infty}$ coefficient values calculated from the vibration signals were developed. The R^2 values of the ${}^{7}Z^{\infty}$ coefficient versus flank wear measurement for tangential and feed direction are 0.87 and 0.86 respectively. The high values of R^2 indicate that there is a very strong correlation between I-kaz multilevel coefficient values and the cutting insert flank wear. The higher the flank wear condition, the higher I-kaz multilevel values calculated for all 8 experiments. Therefore, this SF can be applied as the input parameter for TCM prediction system for flank wear prediction status in the machining process. With this prediction system, the flank wear status could be predicted and the machining process can be stopped before the flank wear exceed the allowed limit.

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