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Development of tool wear machining monitoring using novel statistical analysis method, I-kaz™

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Abstract

The development of tool wear conditioning monitoring method is proposed by applying ceramic piezoelectric sensor mounted on the tool holder in turning machine to monitor vibration signals due to the flank wear progression. Signals captured by the sensor are statistically analysed using Integrated Kurtosis-based Algorithm for Z-notch filter (I-kaz™) technique. This technique produces a 3D graphic form that is quantified by coefficient of I-kaz (Z^{∞}), representing the degree of scattering of data distribution. The result indicates that I-kaz 3D graphic is experiencing contractionary, while Z^{∞} values are getting smaller as the flank wear and cutting speed increases.

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Keywords: *turning; piezoelectric sensor; tool wear monitoring; statistical analysis; I-kaz, flank wear*

1. Introduction

Machining is the most widely used process in manufacturing industry where more than 70% of the industries are using them [1]. Good monitoring on machining especially on its cutting tool can be developed with a better

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understanding on the machine operation, process parameter, type of material and wear of the tool, and tool wear monitoring method. Tool wear monitoring is one of the most critical conditions to ensure smooth machining process [2]. Tool wear is affecting tool life, surface quality, dimension accuracy and machining operation cost [3]. Cutting tools need to be replaced with a new one when they wear out to lower the cost and increase the machining operation performance [4]. Flank wear is the type of wear that set to be the criterion in determining the tool life as it is the major factor in tool failure [5-8].

Recent research focuses on the integration of online tool monitoring system method that can be done automatically [5, 6]. This monitoring system can detect the tool condition well without the need to stop the machine operation to observe the tool. There are 2 monitoring method that introduced in tool wear detection, namely direct and indirect monitoring. Direct monitoring closely related to the optical and visual approach, in which the cutting tool geometry parameter measurement is done [9]. Indirect monitoring involves the use of suitable signal sensors. By using this method, the tool wear can be obtained through cutting force [2, 3, 5, 10, 11], temperature [12, 13], torque and power [14, 15], acoustic emission [16], sound [17] and vibration [5, 7, 18]; This means indirect monitoring suitable to be used for online machining monitoring because it does not interrupt the machining process.

Piezoelectric sensors are one of the indirect monitoring devices that use the piezoelectric effect to measure mechanical input such as force, torque, strain, pressure, acceleration, acoustic emission and vibration by converting them into electrical charge [19]. This study develops a system of indirect tool wear monitoring using low cost sensor which is piezoelectric ceramics. This sensor uses the piezoelectric effect to measure the vibration signal of the tool due to the deflection on the tool holder. Flank wear width, *VB* is measured every time the machining operation is stopped until it reach desired criterion. The produced vibration signal is then being analysed using statistical-based method which is the Integrated Kurtosis-based Algorithm for Z-notch Filter Technique or simply called as I-kaz^{TM} statistical analysis method. Recent study shows that I-kaz^{TM} statistical method was used to study the correlation between I-kaz coefficient and Taylor Tool Life curve for tool wear progression in machining process [20]. An experiment is carried out using CNC turning machine for machine operation to cut the work piece while gather signal data for analysis. Some correlation and relationship are derived from the analysis to predict the wear progression.

2. Methodology

As seen in Fig. 1 (a), the experiment is divided into 2 sections which are machining operation that consist of piezoelectric sensor signal generation and flank wear measurement on the cutting tool. The signal generated from the sensor is analysed using I-kaz^{TM} statistical method and finally correlation between machining signal with the obtained flank wear data is developed. Fig. 1 (b) shows the schematic procedure of experiment for this study.

Three main machining parameters that influence turning operation are cutting speed (V_C), feed rate (f) and depth of cut (D_C). In this study, f and D_C are made constant while V_C is manipulated which means that the variable cutting speed will be the main parameter affecting the machining operation. It is because cutting speed can affects tool life greatly. The values of each of parameter can be seen in Table 1.

Table 1. Sets of experiment with the machining parameters used

Set	Cutting Speed, V_C (m/min)	Depth Of Cut, D_C (mm)	Feed Rate, f (mm/rev)
1	200	0.8	0.15
2	250	0.8	0.15
3	300	0.8	0.15

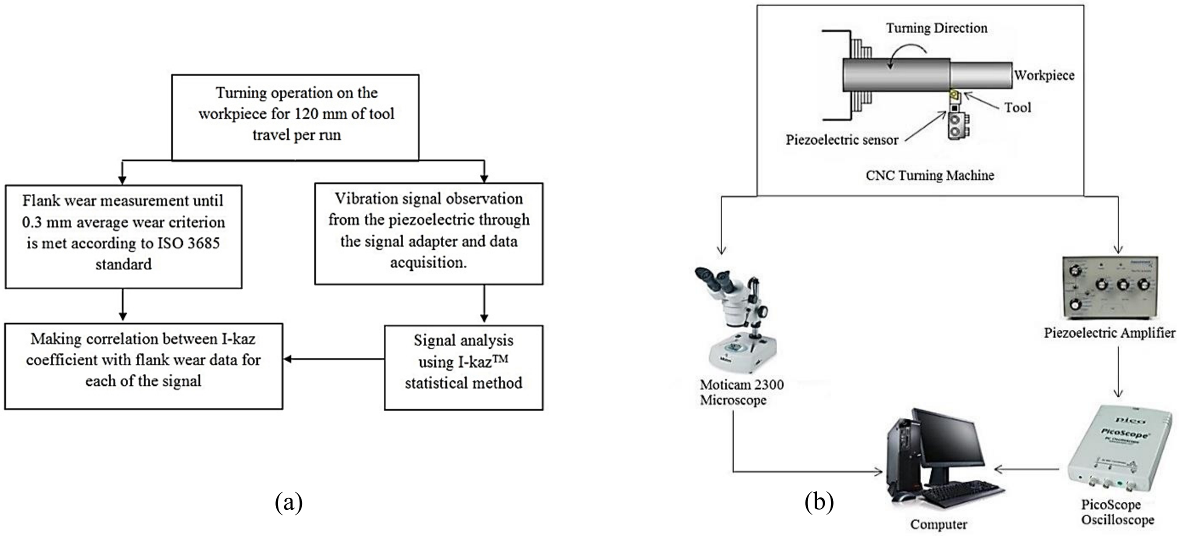


Fig. 1. (a) Flowchart of the research; (b) Schematic illustration of experiment preparatory.

The machining test is carried out using CNC HAAS SL-10 turning machine to turn a work piece for 120 mm of tool travel in dry condition. Material that is used for the work piece is hardened S45C or AISI 1045 medium carbon steel, while the cutting tool is uncoated cemented carbide CNMG-432QM because of its suitability to cut the work piece. Signal observation is done for every turning operation in all sets of the experiment. One piece of ceramic piezoelectric sensor is attached on the tool holder perpendicular with the cutting force (F_C) to measure the deflection on the cutting tool in tangential direction. The raw vibration signal that result from the deflection is amplified using piezoelectric amplifier and adjusted by PicoScope Oscilloscope before displayed in time-frequency domain on computer. Sampling frequency rate is fixed to 200 kHz. Flank wear measurement is made after each 120 mm turning for all three sets of experiment until it reached the average criteria of 0.3 mm according to ISO 3685 standard. Microscope is used to measure the flank wear that form at tool edge. Vibration signals are interpreted to find the relationship between tool wear with signal amplitude and analysed with I-kaz™ statistical analysis method using MATLAB software.

I-kaz™ method is developed based on the degree of data scattering with respect to its centroid for dynamic signal analysis as described by Nuawi et al. [21]. A 3D graphical representation of I-kaz is constructed by decomposing the raw vibration signals into 3 frequency ranges in 3 different axis.

x-axis: Low frequency (LF) range of 0 - 0.25 f_{max}
y-axis: High frequency (HF) range of 0.25fmax - 0.5 f_{max}
z-axis: Very high frequency (VF) range of 0.5fmax f_{max}

where f_{max} is the maximum frequency for the signal. Based from the decomposition of the signal, the coefficient of I-kaz is obtained by using the Equation 1.

$$Z^{\infty} = \frac{1}{n}\sqrt{K_L s_L^4 + K_H s_H^4 + K_v s_v^4} \tag{1}$$

where *n* represent the number of data, K_L,K_H and K_V are the kurtosis while S_L, S_H and S_V are standard deviation for LF, HF, and VF frequency range. I-kaz coefficient is determined to investigate its relationship with tool wear monitoring result.

3. Result and discussion

3.1. Piezoelectric Signal and Tool Wear

The changes of signal amplitude for time and frequency domain at specific flank wear width measurement, *VB* for each set are displayed in Fig. 2. The figure shows that the load produced in time series is described as variable amplitude loading (VAL). For every set in the figure, (a) is the vibration signal at initial formation of flank wear, and (b) is the signal generated at final formation of wear where 0.3 mm wear criterion is met. Based from the figure, vibration signal amplitude that is produced in time domain becoming lower when tool wear increases. Furthermore, the increasing of cutting speed (V_C) also makes the signal amplitude lower. If seen in the frequency domain, peak of spectrum amplitude is in low range of frequency. The result shows that the peak amplitude is decreases when the formation of flank wear is increase until 0.3 mm wear criterion is met. Besides, peak of the signal spectrum in frequency domain shows a clear pattern of declination when the cutting speed is increased set by set.

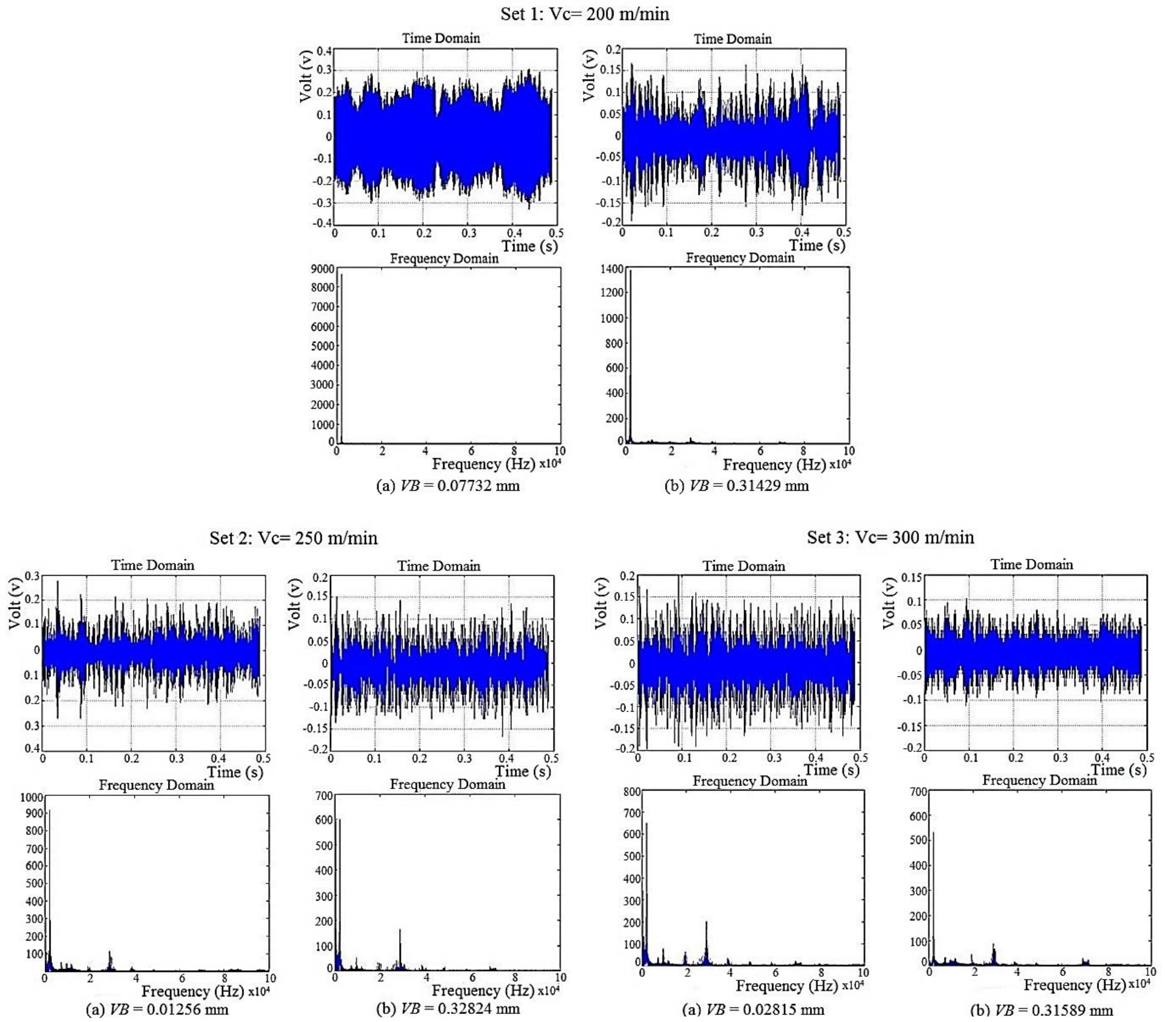
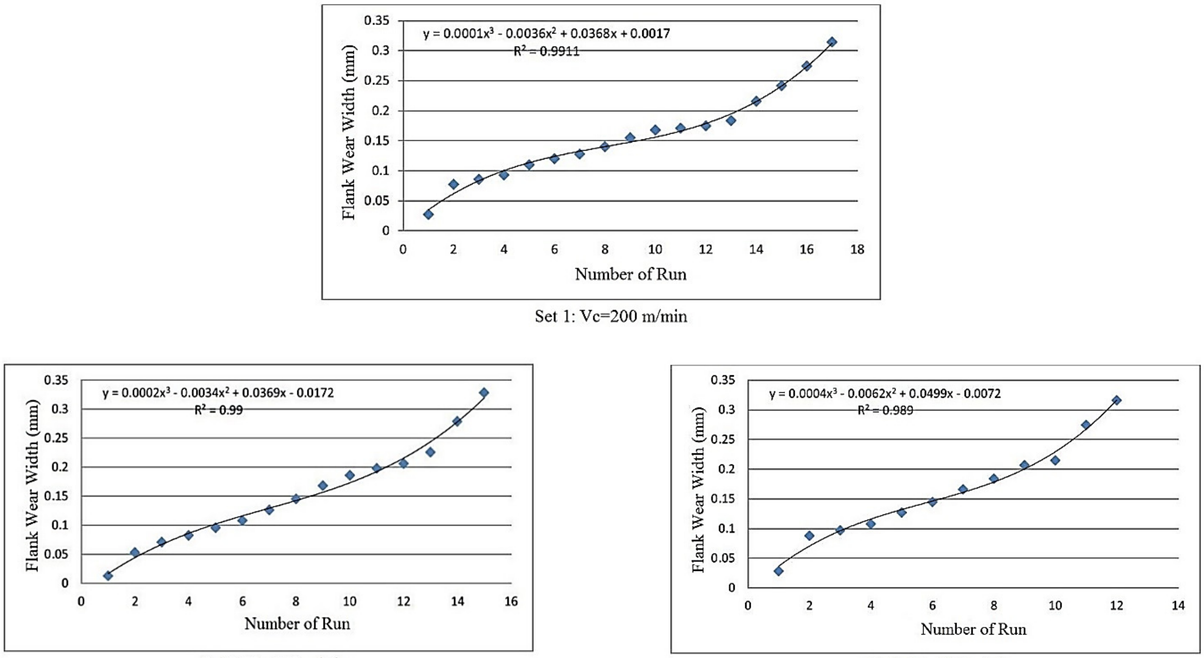


Fig. 2. Piezoelectric signal in time and frequency domain

3.2. Flank Wear Response

Fig. 3 shows the relationship between flank wear data against the number of runs made until 0.3 mm wear criterion is achieved. From the figure, it can be clearly seen that each of the sets show the formation of flank wear width that form a wear curve by the number of runs done. As defined in the theory of tool life, the curve illustrations of the graph is represented by 3 regions, which are initial or break-in period, steady-state and ended with failure region [22]. The turning operation is running smoothly as the wear curve is nearly the same with the theory. Initially the formation of flank wear occurs quickly in early operation. Upon reaching the steady-state region, the wear progression is started to form at uniform rate where it is nearly linear with time. The number of runs depends on the cutting parameters. The formation rate of tool wear is low compared with the initial and failure region. The tool then reaches a point where the wear rate is on the rise at the beginning of failure stage. It took place at the point before wear criterion is achieved. Cutting temperature increases as the surface area of the tool in contact with the work piece become larger due to wear. General efficiency of machining process and the quality of the resulting surface of finish work piece skids. The signal captured from the experiment can be analysed as the validation of the flank wear data is verified through the theory.



Set 1: Vc=200 m/min

Set 2: Vc=250 m/min

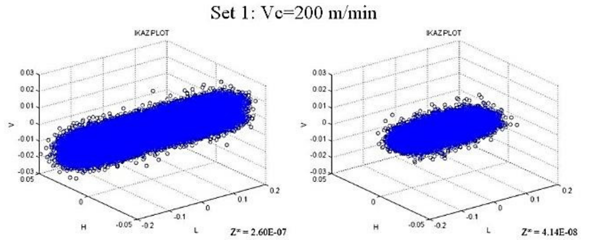
Set 3: Vc=300 m/min

Fig. 3. Graph of flank wear width against number of run in turning operation

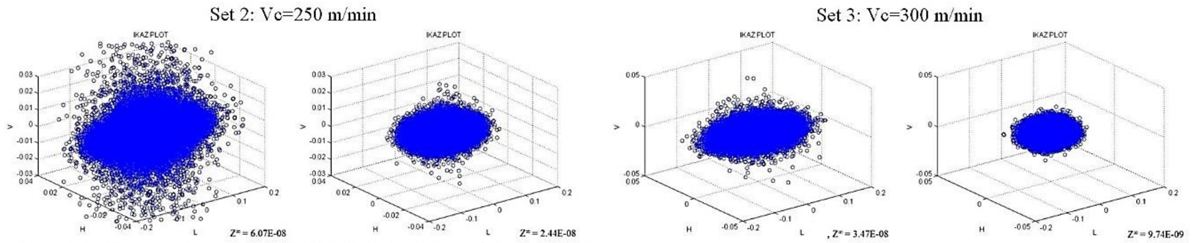
3.3. I-kaz^{TM} Statistical Analysis

Fig. 4 below shows I-kaz 3D graphical representation plot with I-kaz coefficient, Ƶ$^{\infty}$ for all sets of experiment, based on signal data obtained as shown in Fig. 2. I-kaz graphic and Ƶ$^{\infty}$ are obtained from I-kaz^{TM} statistical analysis using MATLAB software. Through observation, the difference in graphics can be seen where the degree of data scattering is reduced when the width of tool wear is increasing. I-kaz graphic is shrinking until wear criterion are met. Ƶ$^{\infty}$ that produced from the signal data showed significant difference for each of the flank wear formation on each set of experiment. The increasing of tool wear width on each run cause Ƶ$^{\infty}$ becomes smaller until 0.3 mm wear criteria is met. It also makes the I-kaz graphic shrink as the degree of data scattering reduce. This is the same with what has been stated by previous studies in which a larger Ƶ$^{\infty}$ value indicates higher degree of data scattering and vice versa [21].

The validity of the piezoelectric sensor signal can be made through the evaluation of morphology or changes in identical graphical form of I-kaz [23]. In set 1 as seen in Fig. 4, at the beginning of wear formation, graphic design shape is like a long cylinder form and after the tool wears out, graphic form still show the same identical shape but shorter. While in Set 2 and Set 3, I-kaz graphic shows large oval form at the beginning and become smaller when it reach wear criterion. Based from that, the signals are confirmed in good condition as the changes in I-kaz graphic are identical.



(a) VB=0.07732 mm, Z^{∞} = 2.60E-07 (b) VB= 0.31429 mm, Z^{∞} = 4.14E-08



(a) VB= 0.01256 mm, Z^{∞} = 6.07E-08 (b) VB= 0.32824 mm, Z^{∞} = 2.44E-08 (a) VB= 0.02815 mm, Z^{∞} = 3.47E-08 (b) VB= 0.31589 mm, Z^{∞} = 9.74E-09

Fig. 4. 3D Graphical representation of I-kaz for beginning and end of tool wear

The values of I-kaz coefficient, Z^{∞} and flank wear width for each set of experiments are summarized in Table 2, while the comparison graph for data correlation between each of them can be seen in Fig. 5. Based from Fig. 5, the values of Z^{∞} becoming lower where the graph curves downward until wear criterion is met. This is because the surface area of contact between the surfaces of work piece with the tool is growing. Resistance to the movement of the tool on the work piece surface decreases. Therefore, it reduces the amplitude of vibration signal, resulting smaller value of Z^{∞}. Same discussion has also been raised on the previous study [21]. Note that the graph curve is high in set 1 experiment, followed by set 2 and ended up with set 3 for the lowest curve. At the time when the flank wear width reaches 0.3 mm, experiment set 1 with cutting speed, V_C=200 m/min shows the highest value of Z^{∞} , followed by set 2 with V_C=250 m/min and lastly set 3 with V_C=300 m/min. Values of Z^{∞} is declining when V_C is increased. This is due to the piezoelectric sensor that detects lower vibration amplitudes at higher cutting speed. It is because the movement between work piece surfaces with the cutting tool is fast, so the contact time between them is smaller. Therefore the vibration amplitude that produced is getting lower at higher cutting speed, V_C, resulting less Z^{∞} value.

Table 2. The values of I-kaz coefficient, Z^{∞} until flank wear criterion are met for all set of experiment

Set 1: 200 m/min		Set 2: 250 m/min		Set 3: 300 m/min	
Z^{∞}	VB (mm)	Z^{∞}	VB (mm)	Z^{∞}	VB (mm)
2.60E-07	0.07732	6.07E-08	0.01256	3.47E-08	0.02815
1.86E-07	0.11985	4.37E-08	0.09541	2.77E-08	0.10761
6.15E-08	0.15469	3.57E-08	0.14504	2.16E-08	0.18356

5.54E-08	0.18346	2.93E-08	0.20611	1.77E-08	0.21468
4.14E-08	0.31429	2.44E-08	0.32824	9.74E-09	0.31589

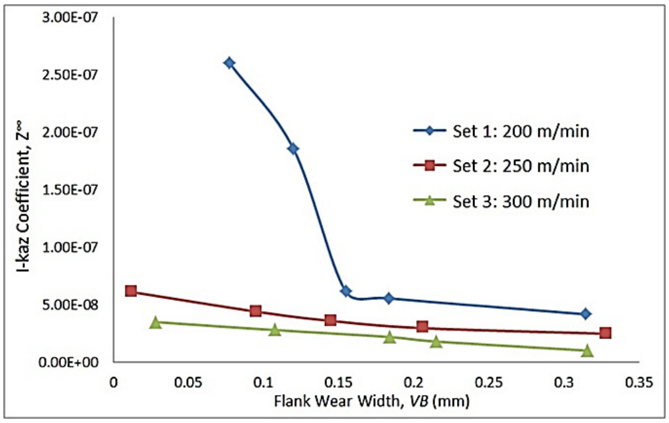


Fig. 5. Graph of I-kaz coefficient, Z^{∞} against flank wear width, *VB* (mm)

4. Conclusion

The development of tool wear machining monitoring using a low cost piezoelectric ceramic sensor has been built and statically analysed using I-kaz^{TM} method successfully. This sensor is small, lightweight, simple and easy to be installed. It is one of the alternatives to measure vibration signal from machining besides using dynamometer or strain gauges. The captured vibration signal is affected by the changes of wear and machining. The signal amplitudes are decrease when the flank wears increase. High cutting speed cause the flank wear to form quickly and shorten the tool life. By using I-kaz^{TM} statistical analysis method, it shows the relationship and correlation between I-kaz coefficients, Z^{∞} values with resultant flank wear width data, *VB*. Z^{∞} values decrease significantly when *VB* increase and falling when cutting speed increases. Determination of whether the criteria of the tool wear is achieved or not in machining process can be implemented with reference based on the Z^{∞} values. Tool condition can then be monitored and the tool can be changed effectively. This monitoring system can be used in industry to increase the quality of work piece surface, reduce cost and maintenance time, and avoiding tool failure during machining.

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