# Statistical Analysis for Detection Cutting Tool Wear Based on Regression Model

Jaharah A. Ghani, Muhammad Rizal, Mohd Zaki Nuawi, Che Hassan Che Haron, Rizauddin Ramli

***Abstract*— This study presents a new method for detecting the cutting tool wear based on the measured cutting force signals. A statistical-based method called Integrated Kurtosis-based Algorithm for Z-Filter Technique, I-kaz was used for developed regression model and 3D graphic presentation of I-kaz 3D coefficient during machining process. The machining tests were carried out on a CNC turning machine Colchester Master Tornado T4 in dry cutting condition, and Kistler 9255B dynamometer was used to measure the cutting force signals, which then stored and displayed in the DasyLab software. A number of force signals from machining was analyzed and each has a characteristic value called I-kaz 3D coefficient. These coefficients have relationship with flank wear land (*VB*). Results of regression model shows the I-kaz 3D coefficient value decreases when the tool wear increases. This result can be used for real time tool wear monitoring.**

***Keywords*— statistical analysis, I-kaz method, tool wear detection**

## I. Introduction

The cutting tool wear is well-known affecting the tool life and the surface quality of the finished product. When tool wear is beyond a certain threshold, the tool fails catastrophically due to excessive stresses and rising thermal within the tool edge caused by large friction forces. In general, the tool wears on the two contact zones. Crater wear occurs on the rake face of the tool where the chip moves under friction and normal loads at elevated temperatures, leading to wear. Since all cutting edges have a finite sharpness, the friction between the flank face of the cutting tool and the freshly cut work surface causes flank wear. The crater wear is usually avoided by selecting a cutting speed and tool material that does not have an affinity to diffusion with the work material [1]. The flank wear, on the other hand, leads to loss of cutting edge, and affects the dimension and surface finish quality. Therefore, importance to develop equation modeling for detection and monitoring cutting tool wear, especially flank wear.

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There are two methods that had been proposed, direct and indirect methods. Direct monitoring methods are such as vision and optical approaches, which measure the geometric parameters of the cutting tool [2], [3]. The direct methods have advantages of capturing actual geometric changes arising from wear of tool. However, direct measurements are very difficult to implement because of the continuous contact between the tool and the workpiece, and almost impossible due to the presence of coolant fluids. The difficulties severely limit the application of direct approach. The indirect methods are achieved by correlating or deducing suitable sensor signals to tool wear states. The advantages are less complicated setup and suitable for practical application. In indirect methods, tool condition is not captured directly, but estimated from the measurable signal feature. This signal feature is extracted through signal processing steps for sensitive and robust presentation of its corresponding state. Indirect methods include such as those based on sensing of the cutting forces, vibrations, acoustic emission, and motor current [4].

In most of the studies done, cutting force signals were widely used as a source for detecting the tool wear and tool failure as studied by Lin and Lin (1996), Dimla et al (1999), Sharhan et al (2001), Kuljanic (2005), and Kang-Jae Lee [5]–[9]. In practice, the application and interpretation of this parameter is diversed with more effort concentrated on studying the dynamic characteristic of the cutting force signal and interpreting its relation to tool wear levels. On the other hand, Oraby and Hayhurst [10] developed models for tool wear and tool life determination using nonlinear regression analysis techniques in terms of the variation of a ratio of force components acting at the tool tip. Srinivas and Kotaiah [11] developed a neural network model to predict tool wear and cutting force in turning operations for cutting parameters of cutting speed, feed and depth of cut. Chen and Li [12] developed a tool wear observer model for flank wear monitoring. They used a correlation between the cutting force components and the flank wear width. It was used in an observer model, which uses control theory to reconstruct the flank wear development from the cutting force signal obtained through online measurements.

Correlation between the cutting force signals with tool wear can be analyzed in many ways. One of them is statistical analysis. Nuawi [13] developed a new statistical-based method of tool wear progression monitoring in turning process, called Integrated Kurtosis-based Algorithm for Z-filter Technique, I-kaz. I-kaz method calculates the related coefficient for the measured machining signals. These coefficients have relationship with flank wear land. The main

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objective of this paper is to develop a new mathematical model for tool wear detection based on cutting force signals using statistical analysis.

## II. Methodology

### A. Experimental Setup and Procedure

The material chosen for machining test was titanium alloy, Ti-6Al-4V. The main characteristics of titanium are high strength, low density and high corrosion resistance to acid, alkali and chlorine. These special characteristics of titanium made it become the first choice in various field such as chemical industry, automotive, biomaterial, shipping and marine applications [14]. Titanium behavior such as chemically reacts with cutting tool at operation temperature, low elasticity modulus and thermal conductivity limits its machinability.

The machining tests were carried out on a CNC lathe machine Colchester Master Tornado T4 in dry cutting condition, and the cutting insert used was Cubic Boron Nitride (CBN). This tool is suitable for turning titanium at high-speed cutting [15]. A Kistler dynamometer type 9255B was mounted on tool post to measure the force signals in the three directions force, namely tangential/cutting force ($F_y$), axial/feed force ($F_x$) and radial/thrust force ($F_z$) as shown as Fig. 1. channels, namely channel I, channel II and channel III. Fig. 2 shows the experimental setup and data acquisition system.

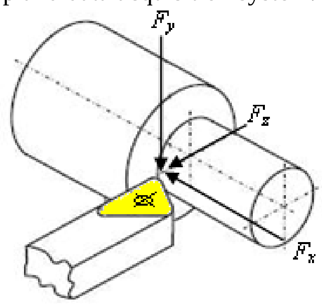


Fig. 1. Force directions on turning process.

Fig. 1 shows cutting force directions in turning process. Cutting force can be represented by channel II, feed force is represented by channel III and radial force is represented by channel I.

Data acquisition process consists of two sets of data collections; i.e. the measurement of the generated dynamic cutting force signals and the flank wear land measurement on the cutting tool edge as shown as Fig 2. Cutting condition were set at cutting speeds of 180 m /min and depth of cut 0.5 mm. Feed rate were set at various feed rates of 0.05 mm/rev and 0.25 mm/rev.

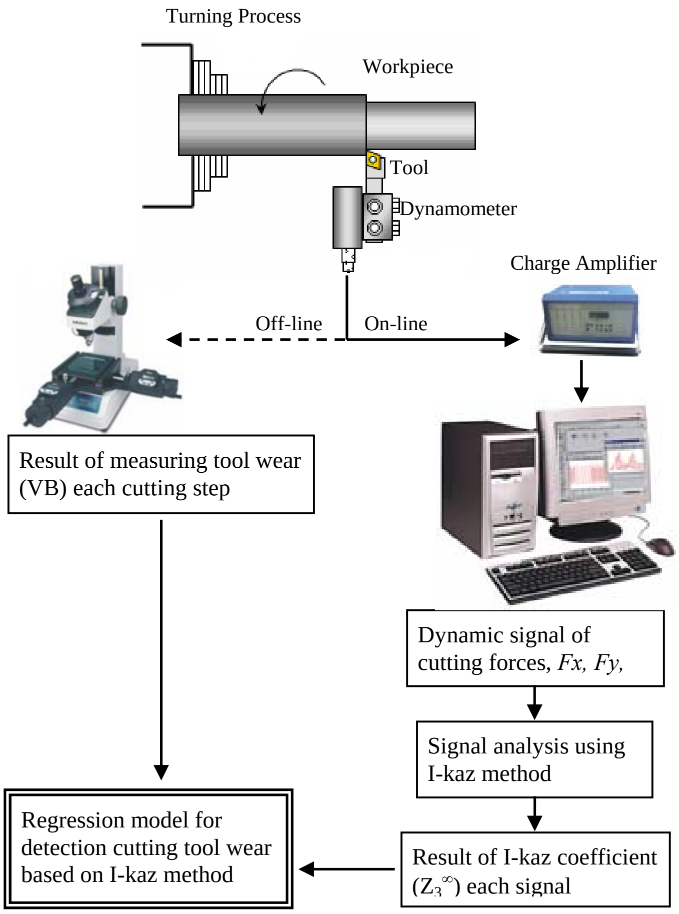


Fig. 2. Experimental setup

Signals generated by Kistler dynamometer model 9255B are dynamic cutting force signal which are captured and stored by DasyLab software. During the turning operation the insert was periodically removed from the tool holder, and the flank wear on the flank face was measured using a Mitutoyo toolmaker's microscope equipped with graduated scale in mm. The measured parameter to represent the progress of wear was tool flank wear *VB*. The turning operation is stopped and the insert was discarded when *VB* reach 0.3 mm. It is a standard recommended value in defining a tool life end-point criterion based on ISO 3685:1993 [16].

### B. Signal Analysis

The signal analysis methods used was a statistical signal processing based on Kurtosis, I-Kaz method. The I-kaz method was pioneered by Nuawi [14]. He studied random or nondeterministic signal characteristics. In order to classify the random signals, the $r$-th order of moment $M_r$ is frequently used. The $r$-th order of moment, $M_r$ for the discrete signal in the frequency band can be written as:

$$M_r = \frac{1}{N}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^r \qquad (1)$$

Where $N$ is the number of data, $x_i$ is data value at the instantaneous point and $\bar{x}$ is the mean. The (1) has brought to

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the derivation of kurtosis. Kurtosis, which is the signal 4th statistical moment, is a global signal statistic which is highly sensitive to the spikiness of the data. For discrete data sets the kurtosis, $K$ is defined as:

$$K = \frac{1}{N\sigma^4}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^4 \qquad (2)$$

Where $N$ is the number of data, $\sigma$ is the variance; $x_i$ is the data value at the instantaneous point and $\bar{x}$ is the mean of the data. The kurtosis value is approximately 3.0 for a Gaussian distribution. Higher kurtosis values indicate the presence of more extreme values than should be found in a Gaussian distribution. Kurtosis is used in engineering for detection of fault symptoms because of its sensitivity to high amplitude events.

Based on kurtosis, the method provides a three dimensional graphical representation of the measured signal frequency distribution. Specifically, the time domain signal was decomposed into three frequency channels. In order to measure the degree of scattering of the data distribution, the I-kaz coefficient calculates the distance of each data point from the signal's centroid. I-kaz coefficient was defined as:

$$I - kaz\ \text{3D}\ coef = \sqrt{\frac{1}{N}\left(M_4^I\right) + \frac{1}{N}\left(M_4^{II}\right) + \frac{1}{N}\left(M_4^{III}\right)} \qquad (3)$$

Where $N$ is the number of data and $M_4^I$ , $M_4^{II}$ , $M_4^{III}$ are the 4-th order of moment in channel-I, channel-II and channel-III respectively. The I-kaz coefficient was substituted in (4) and the symbol of $Z_3^\infty$ was used to represents the I-kaz coefficient.

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

Where $N$ is the number of data, $K_I$, $K_{II}$ and $K_{II}$ are the kurtosis of signal in ch-I, ch-II and ch-III and $s_I$, $s_{II}$ and $s_{III}$ are the standard deviation of signal in ch-I, ch-II and ch-III respectively.

## III. Result and Discussion

The recorded machining force components values verse flank wear land when turning Ti-6Al-4V with CBN tool inserts under dry cutting machining at various feed rate of 0.05 mm/rev and 0.25 mm/rev are shown in Figures 3 and 4 respectively. Cutting speed and depth of cut were set at 180 m/min and 0.5 mm respectively. Fig. 3 and 4 show that the cutting force is very sensitive with the increase in the value of flank wear. When flank wear increases, the cutting force also increases. The graph also shows that the tangential force also known as main cutting force (Fy) is very dominant force on the metal cutting process. These results are in agreeable with Wang et al. [17]. They modeled a hybrid cutting force for Titanium alloys based using FEM simulation based on Oxley's theory. While, Sauza et al [18], analyzed the cutting force machining cast iron material.

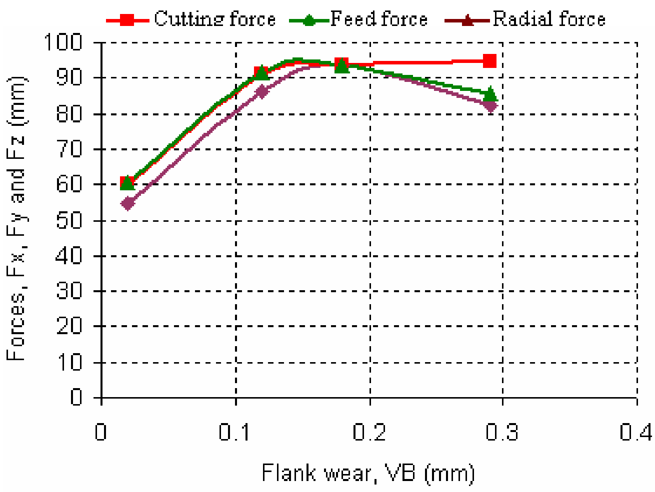


Fig. 3. Variation of machining forces with flank wear at feed rate 0.05 mm/rev

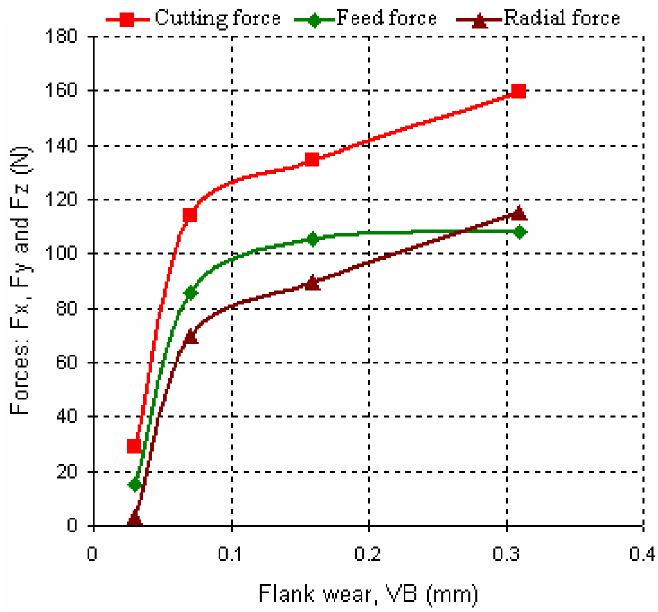


Fig. 4. Variation of machining forces with flank wear at feed rate 0.25 mm/rev

The influence of feed rate in machining forces is also very significant. At feed rate of 0.05 mm/rev, the cutting force reach about 96 N at flank wear of approximately 0.29 mm, whereas at feed rate of 0.25 mm/rev the cutting force can reach to 160 N or has been increase to about 60%. These results are in agreement with Seker et al [19]. They investigated the effect of feed rate on the cutting forces when machining ST 44 steel workpiece material.

Every machining signal has its own characteristics of feature result due to effect of increasing flank wear. These characteristics can be analyzed using statistical method that has been introduced by Nuawi et al [13] called I-kaz method. In this method, components of machining force, Fx, Fy and Fz

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are converted into channel I, channel II and channel III respectively. Therefore, the calculation of the value of the signal characteristic is called I-kaz 3D coefficient indicated as $Z_3^\infty$. Fig. 5 shows I-kaz 3D coefficient versus flank wear at feed rate 0.05 mm/rev and 0.25 mm/rev.

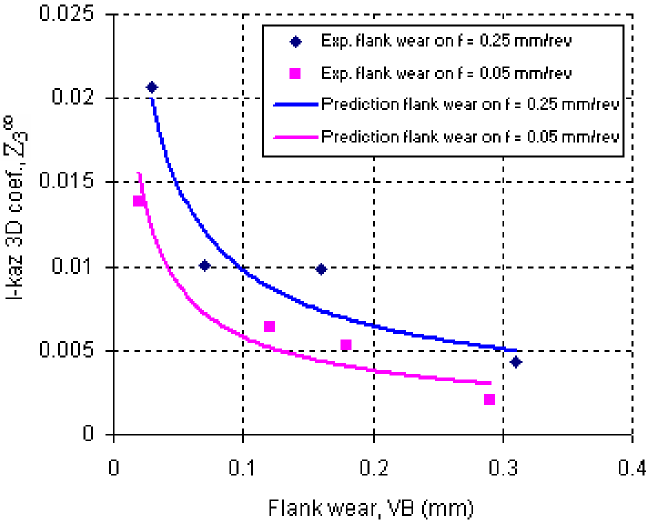


Fig. 5. Curve fitting of I-kaz coefficient, $Z_3^\infty$ versus flank wear, VB.

At the first cutting, the value of $Z_3^\infty$ is about 0.015 – 0.02, but at the end of cutting or when the flank wear reached about 0.3 mm, the value of $Z_3^\infty$ is about 0.0025 – 0.0045. The trend of the curve indicates that a decrease in coefficient of $Z_3^\infty$ when flank wear increases. Decline in the coefficient of $Z_3^\infty$ is in accordance with the trend of power-law curve fit. The performance of correlation of curve fit ($R^2$) at feed rate 0.05 mm/rev and 0.25 mm/rev are 0.86 and 0.89 respectively. From the results of curve fitting, a new equation is derived, which can be used to detect the flank wear. The equation based on power-law curve fitting is shown as equation (5) below.

$$y = ax^{-n} \qquad (5)$$

Where $y$ is the value of I-kaz 3D coefficient, $Z_3^\infty$. $a$ and $n$ are constants coefficient which depend on cutting condition, and $x$ is the value of flank wear, $VB$. Therefore, equation (5) can be written as:

$$Z_3^\infty = a(VB)^{-n} \qquad (6)$$

This equation can be used to detect flank wear by using captures force signals and calculates its characteristic based on I-kaz method. Therefore, equation (6) can be written simply as:

$$VB = \left(\frac{a}{Z_3^\infty}\right)^{1/n} \qquad (7)$$

According to graph on Fig. 5 constants coefficient on feed rate 0.05 mm/rev is derived:

$$VB = \left(\frac{0.0014}{Z_3^\infty}\right)^{1/0.57} \qquad (8)$$

And on feed rate 0.25 mm/rev is:

$$VB = \left(\frac{0.0025}{Z_3^\infty}\right)^{1/0.60} \qquad (9)$$

As mentioned in the previous section, I-kaz method provides a three dimensional graphical representation of the measured signal distribution as shown as Fig. 6.

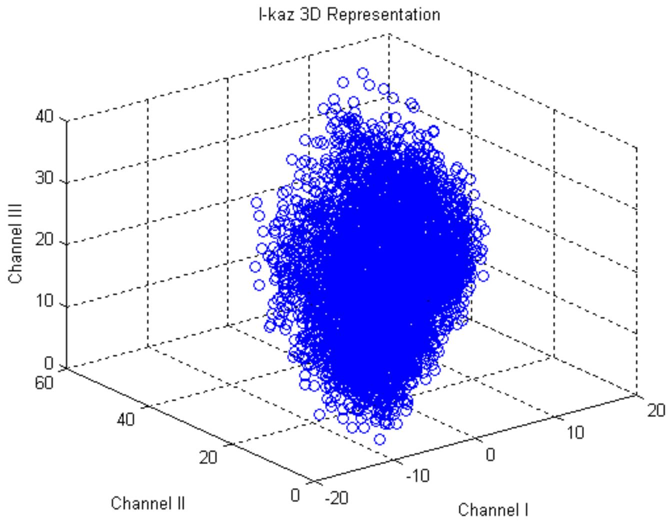


Fig. 6. 3D representation of cutting force data distribution at the first cutting or flank wear about 0 – 0.10 mm

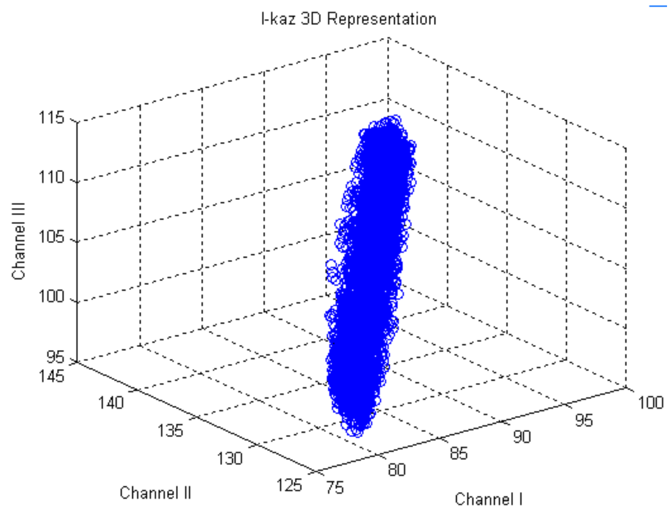


Fig. 7. 3D representation of cutting force data distribution at the flank wear about 0.10 – 0.20 mm

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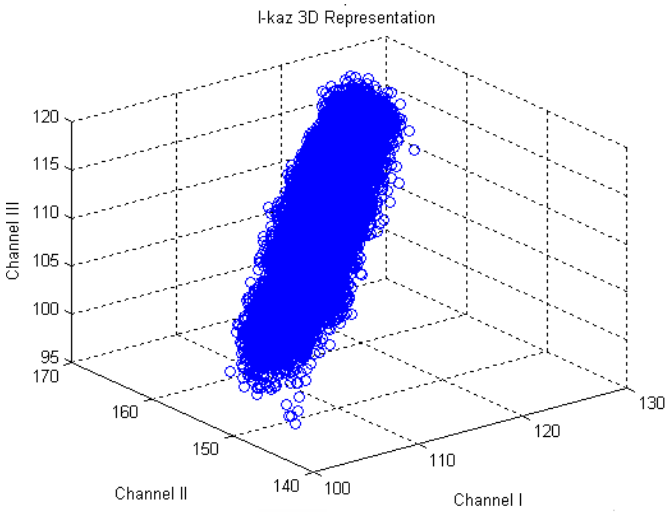


Fig. 8. 3D representation of cutting force data distribution at the flank wear about 0.20 – 0.30 mm

Fig. 6, 7 and 8 show the distribution of feed force data in channel I, channel II is the distribution of main cutting force data and channel III is the distribution of radial force data. These figures show the alteration range of cutting force signal distribution. The range is contractionary with increasing in flank wear value. The same result is obtained with the $Z_3^\infty$ value. Therefore, the result of statistical analysis based on I-kaz method can be used for detection and prediction flank wear on turning processes.

## IV. CONCLUSIONS

This paper discussed on cutting tool wear detection and prediction using I-kaz method. Tool wear is a time dependent process in which tool wear increases gradually with the cutting time. From the analysis and calculation of I-kaz 3D coefficient ($Z_3^\infty$), the relationship is obtained between the I-kaz 3D coefficient and the flank wear value, and is given by: $Z_3^\infty = a(VB)^{-n}$. Where $a$ and $n$ are coefficient that the value depend on cutting condition that are cutting speed, feed rate and depth of cut. From this equation, at the same cutting condition, a new model for detection and prediction flank wear land is obtained as:

$$VB = \left(\frac{a}{Z_3^\infty}\right)^{1/n}$$

The value of $Z_3^\infty$ was obtained from signal acquisition during turning process. This result can be used for real time detection of actual status of flank wear on turning processes.

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