Integration of I-kaz Coefficient and Taylor Tool Life Curve for Tool Wear Progression Monitoring in Machining Process

Nuawi M. Z., Lamin F., Nor M. J. M., Jamaluddin N., Abdullah S., Nizwan C. K. E.

***Abstract*—** This paper presents a new statistical-based method of tool wear progression monitoring in turning process, called Integrated Kurtosis-based Algorithm for Z-filter Technique, I-kaz. The I-kaz method calculates the related coefficient for the measured machining signals. The input data of the I-kaz method was acoustic signal that was generated during machining process, which was in the ultrasonic frequency range. Ultrasonic signal was measured as a tool of sensing element to study the flank wear on the cutting tool edge at various cutting parameters. The flank wear progression was monitored by the value of the I-kaz coefficient integrated with the Taylor Tool Life curve. The resulting trend of I-kaz coefficient on the flank wear rate in the Taylor Tool Life curve was effective in observing the flank wear progression. In addition, the technique was reliable for both low and high speed cutting that could help to predict tool life.

***Keywords*—** Flank wear, I-kaz, Tool condition monitoring, Tool life, Turning, Ultrasonic.

I. Introduction

TOOL wear is a complex phenomenon occurring in different metal cutting processes [1]. Generally, worn tools adversely affect surface finish of the machined part. By continuous operation, the worn tools may fail due to plastic deformation, mechanical breakage, cutting edge blunting, and tool brittle fracture or due to the rise of the interface temperatures. Therefore, there is a need to develop tool wear condition monitoring systems, which alert the operator to the level of tool condition, thereby avoiding undesirable consequences [2]. Besides, maintaining acceptable flank wear below the rejection criterion is very essential to avoid excessive surface and sub-surface damages on machined components.

Various methods for tool wear monitoring have been proposed in the past [3-6]. even though none of these methods was universally successful due to the complex nature of the machining processes. Direct measurement of tool wear using optical methods can only be applied when cutting tools are not in contact with the work piece [5]. Meanwhile, the performance of monitoring systems based on cutting force and acoustic emission are still far behind expectations, which the primary reason are caused by its high cost and low performance ratio [4]. In order to overcome these disadvantages, ultrasonic signal-based technique was introduced by Nuawi *et al.* [7] to monitor the tool wear condition.

Increasingly, facilities professionals are using ultrasonic technology in conjunction with other inspection tools. This method allows for thorough inspection of all equipment without interruption of service. The major advantage of using ultrasonic signal to monitor cutting tool condition is that ultrasound wave is directional [8]. Ultrasound travels in a straight line and this is such a special behaviour of ultrasound signal. Besides, ultrasound provides early warning of impending mechanical failure.

According to NASA research, ultrasonic bearing monitoring can warn of wear and imminent failure before the condition can be predicted from changes in vibration or temperature [8]. Furthermore, ultrasonic signal are ideal for use in loud and noisy environment. As the CNC machine and its environment are noisy, the frequency range of the measured signal is much higher than that of the machine vibrations and background noise. Most of the noise component does not interfere with the cutting operation. Therefore, ultrasonic instrument support and enhance other predictive maintenance technologies, such as vibration analysis.

Realising the advantages of ultrasonic signal-based technique, it leads to the development of an ultrasonic signal-based tool wear monitoring method. As the machining

Manuscript received April 30, 2007. This work was supported by University Kebangsaan Malaysia and Ministry of Science, Technology and Innovation, through the fund of 03-01-02-SF0303. Revised received Nov.1, 07.

Nuawi M. Z. is with the Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia (tel: 603-89216507; fax: 603-89259659; e-mail: zaki@vlsi.eng.ukm.my).

Lamin F. is with the Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia (tel: 603-89216530; fax: 603-89259659; e-mail: fauziana@vlsi.eng.ukm.my).

Nor M. J. M. is with the Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia (tel: 603-89216016; fax: 603-89259659; e-mail: jailani@vlsi.eng.ukm.my).

Jamaluddin N. is with the Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia (tel: 603-89216509; fax: 603-89259659; e-mail: nordin@vlsi.eng.ukm.my).

Abdullah S. is with the Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia (tel: 603-89216518; fax: 603-89259659; e-mail: shahrum@vlsi.eng.ukm.my).

Nizwan C. K. E. is with the Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia (tel: 603-89216530; fax: 603-89259659; e-mail: ckeddy@vlsi.eng.ukm.my).

operation emit consistent sound patterns under normal operation, the method was designed to identify the tool wear patterns. These patterns can be defined and recognized and changes in these patterns can be identified as tool begins to wear or deteriorate. This paper presents a new technique of ultrasonic signal-based tool wear monitoring method for turning of Aluminium alloy by considering the wear rate effect at various cutting parameter.

II. LITERATURE BACKGROUND

A. Signal Analysis

A measured signal is commonly consist of variation of amplitude, frequency, phase and energy. Signals can be divided into two main categories which are deterministic and nondeterministic. A deterministic signal can be described by a mathematical relationship between the value of the function and time. Many signals in nature exhibit random or nondeterministic characteristics which provide a challenge to analyse using signal processing techniques. 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:

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

where N is the number of data, x_i is data value at the instantaneous point and is the mean. The Eq. (1) has brought to 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:

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

where N is the number of data, σ 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 I-kaz method was pioneered by Mohd Zaki (2005). The method provides a three dimensional graphical representation of the measured signal frequency distribution. Specifically, the time domain signal was decomposed into three frequency bands, which x-axis is low frequency (*LF*) range of 10-20 kHz, y-axis is high frequency (*HF*) range of 20-50 kHz and z-axis is very high frequency (*VF*) range of 50-100 kHz. 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 [9]. I-kaz coefficient was defined as:

$$I-kaz\ coefficient = \sqrt{\frac{1}{N}\left(M_4^L\right) + \frac{1}{N}\left(M_4^H\right) + \frac{1}{N}\left(M_4^V\right)} \tag{3}$$

where N is the number of data and M_4^L, M_4^H, M_4^V are the 4th order of moment in *LF*, *HF* and *VF* range respectively. The I-kaz coefficient can be simplified as in Eq. (4) and the symbol of $Ƶ^\infty$ was used to represents the I-kaz coefficient.

$$Ƶ^\infty = \frac{1}{N}\sqrt{K_L s_L^4 + K_H s_H^4 + K_V s_V^4} \tag{4}$$

where N is the number of data, K_L, K_H and K_V are the kurtosis of signal in *LF*, *HF* and *VF* range and s_L , s_H and s_V are the standard deviation of signal in *LF*, *HF* and *VF* range respectively.

B. Cutting Tool Flank Wear

Cutting tools are subjected to an extremely severe rubbing process. There are in metal-to-metal contact between the chip and work piece, under conditions of very high stress at high temperature. The situation is further aggravated due to the existence of extreme stress and temperature gradients near the surface of the tool. During machining, cutting tools remove material from the component to achieve the required shape, dimension and surface roughness. However, wear occurs during the cutting action, and it results in the failure of the cutting tool. When the tool wear reaches a certain extent, the tool or active edge has to be replaced to obtain the desired cutting specification.

The high contact stress between the tool rake-face and the chip causes severe friction at the rake face, as well as friction between the flank and the machined surface. The result is a variety of wear patterns and scars, which can be observed at the rake face and the flank face. Crater wear, flank wear, notch wear, chipping and ultimate failure are the wear patterns that may occur at the tool edge during machining process. In machining, two wear modes most frequently discussed are flank wear and crater wear. Flank wear receives much more attention because it is easier to measure and the mechanism of the material loss is thought to be better understood for most machining situations [10].

Wear on the flank or relief face is called flank wear and results in the formation of a wear land. Wear land formation is not always uniform along the major and minor cutting edges of the tool. Flank wear most commonly results from abrasive wear of the cutting edge against the machined surface. Flank wear can be monitored in production by examining the tool or by tracking the change in size of the tool or machined part.

The typical stages of tool wear in normal cutting situation consist of three stages which are an initial rapid, a relatively steady state and the final rapid stage. Stage 1 is the preliminary wear region where the cutting edge is rounding. Wear is caused by micro-cracking, surface oxidation and carbon loss layer, as well as micro-roughness at the cutting tool tip in manufacturing. For the new cutting edge, the small contact area and high contact pressure will result in high wear rate. Stage 2 is the steady wear region, where the micro-roughness is improved. In this region the wear size is proportional to the cutting time and the wear rate is relatively constant. Stage 3 is severe wear region, where the ultimate or catastrophic wear occurs. Flank wear and chipping will increase the friction, so that the total cutting force will increase. Consequently, the tool loses its cutting ability. The component surface roughness will be increased, especially when chipping occurs. Flank wear will also affect the component dimensional accuracy and the shape of the machined component. In practice, this region of wear should be avoided.

III. METHODOLOGY

The material chosen for the test samples was titanium alloy, 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.

The titanium behaviour which has chemical reaction with cutting tool at tool operation temperature, low elasticity modulus and thermal conductivity limits its machinability. Uncoated carbide, Cubic Boron Nitride (CBN/PCBN) and Poly Crystalline Diamond (PCD) can be used to cut titanium. Uncoated carbide is suitable for low speed cutting. Otherwise, CBN/PCBN is suitable for high-speed cutting [11-12]. Therefore, as low-speed cutting was carried out, uncoated carbide cutting tool, SECOVBMT160408-F2 HX was chosen as it is sufficient to do the cutting.

The machining tests were carried out on a Cincinnati Milacron 200T Turning Centre machine in dry condition. In general, changes in cutting speed, feed rate and depth of cut affect the signal generated during the turning process. Those parameters influence the tool wear by a large extent. Therefore, the effect of cutting speed, feed rate and depth of cut were taken into consideration in order to study the wear pattern at the different wear rate. Table 1 presents the 18 sets of cutting parameter chosen for the test samples.

Data acquisition process consists of two different data collections which the first is the measurement of the generated signal and the second is the flank wear measurement on the cutting tool edge. Microphone Gras 40BE with frequency range of 10 kHz to 100 kHz was used to measure the generated signal. Once the desired signal was measured, it was transferred to digital oscilloscope Yokogawa DL1400. Meanwhile, cutting tool was dismantled from its holder after each cutting time to observe the progression of flank wear. This was done using the optical microscope Mitutoyo and the value of the formed flank wear was recorded.

Table 1 Test samples used for the machining test including cutting speed, *Vc*, feed rate, *f* and depth of cut, *Dc*.

Cutting speed, *Vc* (*m/min*)	Feed rate, *f* (mm/rev)	Depth of cut, *Dc* (mm)	No. of test sample
90	0.2	0.15	18
90	0.25	0.15	17
105	0.2	0.15	14
105	0.25	0.15	13
120	0.2	0.15	16
120	0.25	0.15	15
90	0.2	0.2	1
90	0.25	0.2	2
105	0.2	0.2	8
105	0.25	0.2	9
120	0.2	0.2	7
120	0.25	0.2	6
90	0.2	0.25	10
90	0.25	0.25	5
105	0.2	0.25	11
105	0.25	0.25	12
120	0.2	0.25	4
120	0.25	0.25	3

The machining operation was repeated using the same set of test sample until the value of flank wear reach the acceptable flank wear value of 0.3mm. It is a standard recommended value in defining a tool life end-point criterion based on ISO 3685:1993 [13]. Signals obtained were then being analyzed by plotting the flank wear versus number of cutting curve. The calculation of Ƶ$^{\infty}$ has been done and the relation between the Ƶ$^{\infty}$, flank wear and the number of cutting has been observed.

IV. RESULTS AND DISCUSSIONS

Previous studies on uncoated and coated tools [5] revealed that the cost of machining might be optimized using wear maps, which offered global perspectives on tool wear under different machining conditions. It was shown that properly constructed wear maps enabled the judicious selection of machining conditions that would achieve an optimal balance between an acceptable rate of tool wear and material removal rate for maximum productivity. Thus, next plots were done in order to observe the trend of wear rate progression at certain machining condition.

The value of flank wear was plotted against the number of cutting for every test sample. As a result, a cubic curve was obtained as shown in Fig. 1. The changes on the slope of the curve explain the rate of flank wear that built on the cutting tool edge during the machining process. This curve is dominant with the typical stages of tool wear in normal cutting situation (Taylor curve), which highlights the three stages in the escalation of wear rate (break-in period, steady state wear region and failure region).

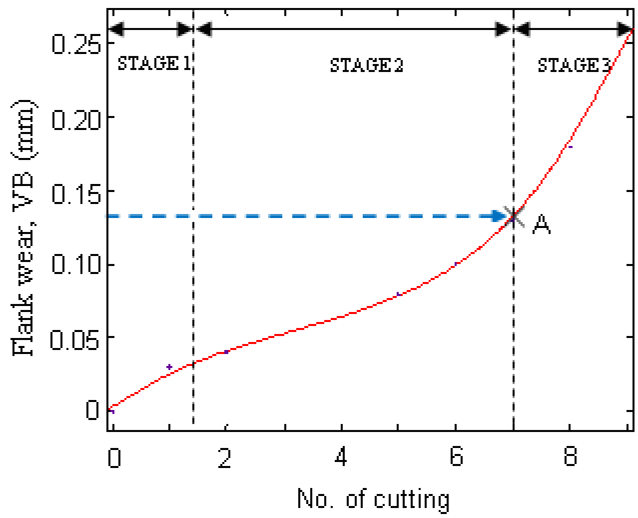


Fig. 1 The plot of flank wear versus number of cutting for the tenth test sample.

Theoretically, based on the Taylor curve the build-up edge (BUE) was took place at the cutting tool edge at the first transition point. The flank wear value was gradually increased because of the BUE formation. The BUE was grown until the wear rate escalation exceeds the second transition point, where the failure region begins. After that, (at the final rapid stage) the BUE has been removed, the cutting edge chipped and the cutting tool should be replaced in order to avoid surface damage.

Since the work piece surface quality was highly affected by the BUE, the determination of the second transition point was essential. The analysis of the cutting tool condition at a certain time can be done by utilising the I-kaz coefficient analysis. Based on the Eq. (3), the value of $\not{Z}^{\infty}$ has been calculated for every signal measured during the cutting process. The plot of $\not{Z}^{\infty}$ versus flank wear value obtains a quadratic polynomial curve as shown in Fig. 2.

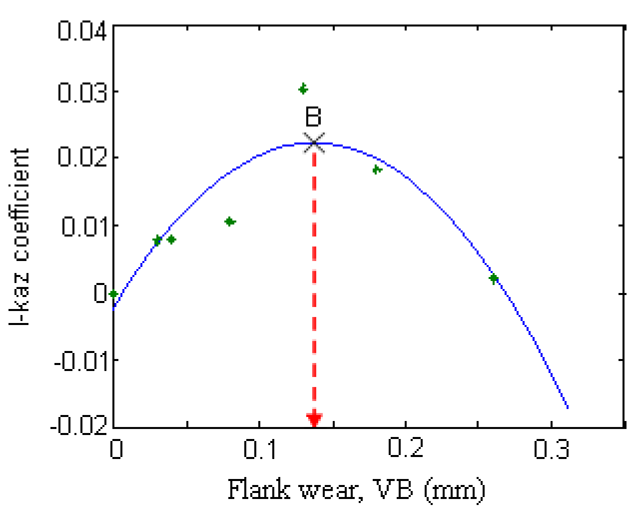
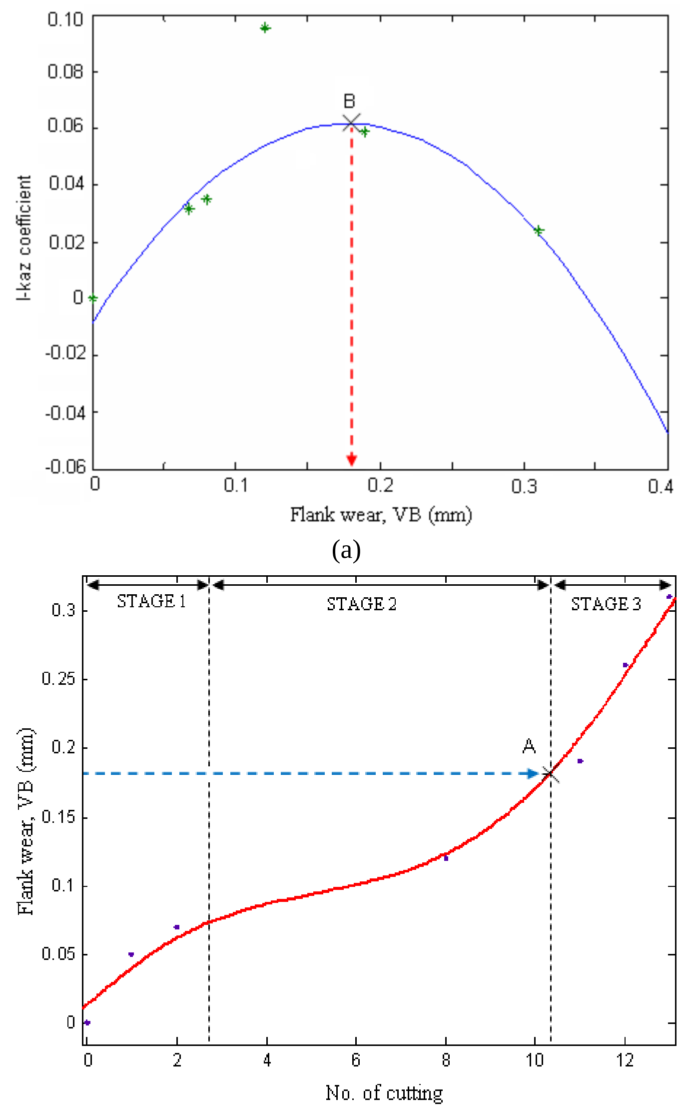


Fig. 2 the plot of $\not{Z}^{\infty}$ versus the value of flank wear for the tenth test sample (Vc = 90 m/min, f = 0.2, Dc = 0.25)

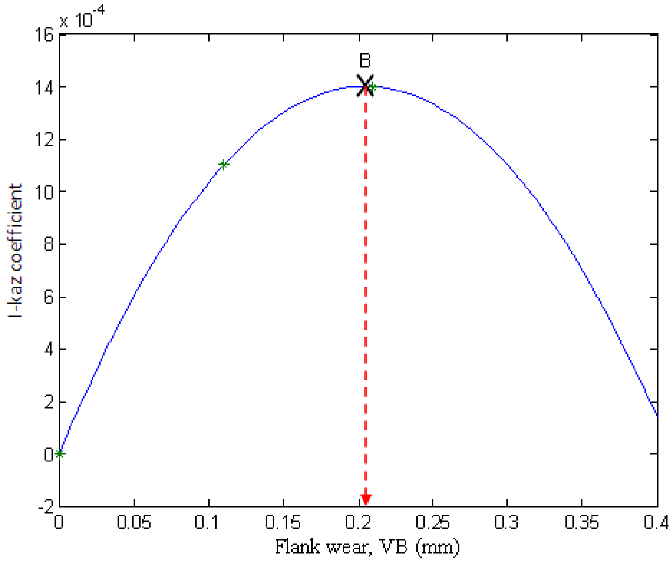
As observed, the quadratic curve has a significant relation with the cubic curve for each test sample respectively. Based on the overall comparison, the maximum point of the quadratic curve indicates the transition point of the steady-stare wear region into the failure region on the cubic curve. For example, B which is the maximum point of the quadratic curve (see Fig. (2)) indicates the transition point of wear rate (point A) on the cubic curve (see Fig. (1)). The maximum point of the quadratic curve which is 0.0223 was obtained when the flank wear of 0.1377 mm was formed at the cutting tool edge. Meanwhile, based on the quadratic curve the 0.1377 mm of flank wear occurs at the seventh cutting. This means, the cutting process using the tenth test sample should be stopped at the seventh cutting. After the seventh cutting, the flank wear was entered the failure region and this will consequently rise the risk of cutting tool failure and the quality of the machined surface. Thus, as the critical point of wear rate can be determined, the decision of tool replacement could be done accordingly.



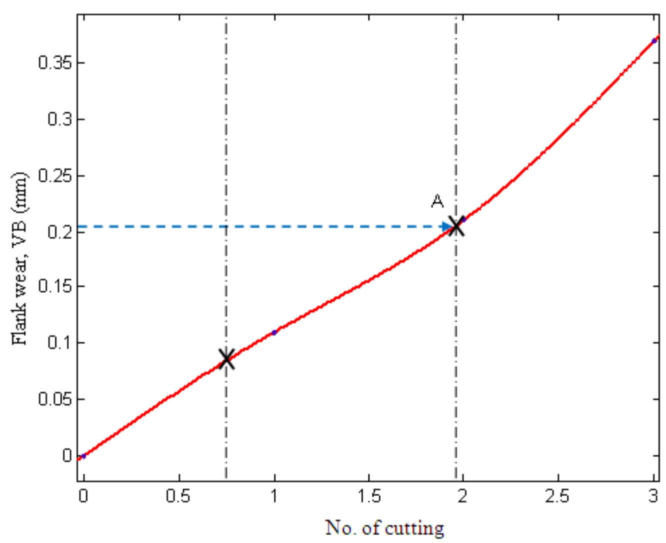
(a)

(b)

Fig. 3 The second test sample: (a) I-kaz coefficient versus flank wear curve, (b) Flank wear versus number of cutting



(a)



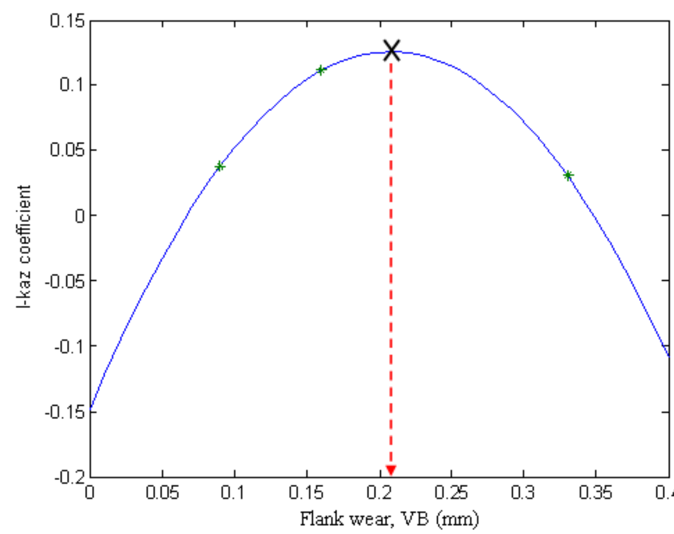
(b)

Fig. 4 The plots of the eleventh test sample: (a) I-kaz coefficient versus flank wear curve, (b) Flank wear versus number of cutting.

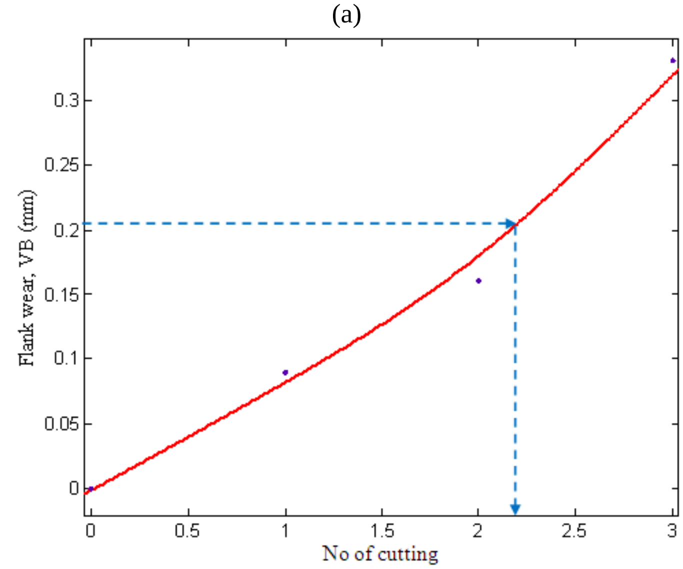
The same scenario can also be observed in other test samples. Some examples can be observed in the Fig. (3) and Fig. (4), i.e. the second and eleventh test sample. Again, the maximum point of the quadratic curve was obtained and it proves that the point indicates the onset of the cutting tool failure region in the Taylor curve. As a result it can be known that the cutting should be stopped at the tenth cutting and the second cutting accordingly.

For the cutting that using the high cutting speed, *Vc* of 120 m/min such as the third, fourth, sixth and seventh test sample, the three regions of the Taylor curve cannot be obviously determined. It can be seen in Fig. (5) that the turning operation with 120 m/min *Vc* obtains an approximately straight line of the Taylor curve. The Taylor curve exhibits a sudden increase of flank wear until the tool life criterion of 0.3 mm exceeded. The result has proven that the Taylor curve was unable to indicate the critical transition points between the three typical regions for the cutting that using *Vc* higher than 120 m/min.

Since the plot of Z^{∞} against the flank wear value consistently obtains the quadratic curve for all test samples, the approach can be applied for the cutting that using high cutting speed. Indirectly, the limitation of the Taylor curve in verifying the onset of the failure region transition point for the high speed cutting can be eliminated. The flank wear transition point of the failure region can be determined by the maximum point of the quadratic curve. This can be obviously observed in the example of the fourth and the seventh test samples as presented in Fig. (5) and (6).



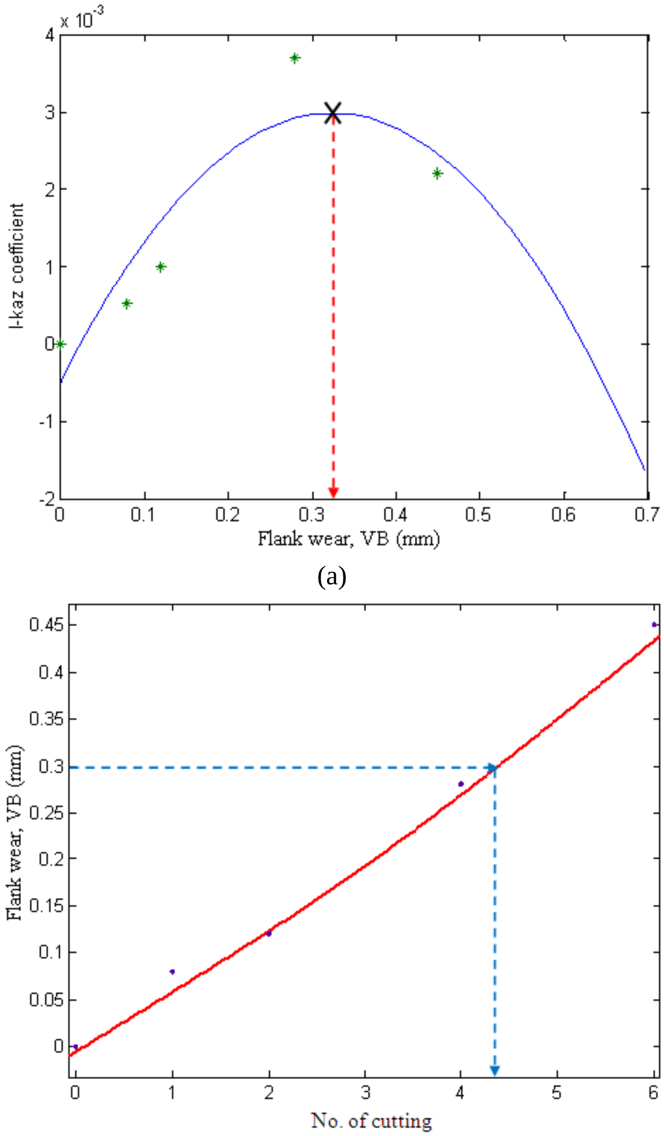
(a)



(b)

Fig. 5 The plots of the fourth test sample: (a) I-kaz coefficient versus flank wear curve, (b) Flank wear versus number of cutting

For the fourth test sample, the maximum point of the quadratic curve was obtained when the flank wear width was 0.2076 mm. This value was then be used to determine the critical point of the flank wear. Based on the Taylor curve, it can be seen that the safe period of cutting using the fourth test sample can only be done until shortly after the second cutting. This has proven that the cutting parameter combination of 0.25mm *Dc*, 0.2 mm/rev *f* and *Vc* 120 m/min was poor to cut the Titanium alloy.



(a)

(b)

Fig. 6 The plots of the seventh test sample: (a) I-kaz coefficient versus flank wear curve, (b) Flank wear versus number of cutting

In addition, the seventh test sample exhibits the similar scenario. The maximum number of cutting that can be achieved using the seventh test sample was four. Comparatively, the number of cutting that can be achieved was a bit higher than the second test sample. This is because the seventh test sample was comprised of lower cutting parameters (*Dc* = 0.2mm, *f* = 0.2 mm/rev, *Vc* = 120 m/min) compared to the second test sample. Means, the rate of flank wear was comparatively lower than the second test sample. It can therefore be concluded that the quadratic curve that utilising the Ƶ$^{\infty}$ has shown it unique capability in determining the safe period of cutting.

V. CONCLUSION

This paper discussed on the tool life monitoring using the I-kaz method. The resulting trend of the Ƶ$^{\infty}$ analysis was efficient in determining the onset of the cutting tool failure region. The transition point can be monitored based on the maximum value obtained from the plot of the Ƶ$^{\infty}$ against flank wear. Accordingly, the specific number of cutting that can be achieved for every test sample has been determined and the specific period of the safe cutting has been verified. Besides, the presented approach has improved the Taylor curve which was unable to exhibit the three typical wear regions for the cutting that using more than 120 m/min of cutting speed. Similarly, the critical point of flank wear can be determined by the maximum value of the quadratic curve as the plot of the Ƶ$^{\infty}$ versus flank wear consistently obtains the quadratic curve. Thus, this method was proposed to be applied integrated with the Taylor Tool Life curve as an alternative technique to monitor the cutting tool wear progression during the machining process. By efficiently utilizing the graphical representation in a production line, an intelligent system can manage the issues concerning quality of machined product, machining parameters and tool life optimization and thus provides production guidance accordingly.

ACKNOWLEDGMENT

The authors wish to express their gratitude to University Kebangsaan Malaysia and Ministry of Science, Technology and Innovation, through the fund of 03-01-02-SF0303, for supporting this research.

REFERENCES

[1] Li, X., Venuvinod, P. K., Djorjevich, A., Liu, Z., "Predicting Machining Errors in Turning Using Hybrid Learning". *International Journal of Advanced Manufacturing Technology*, vol 18, no. 12, pp. 863–872, 2001.

[2] Garret, O., Young, P., Kevin, K., Byrne, G., "Towards the improvement of tool condition monitoring systems in the manufacturing environment". *Journal of Material Processing Technology*, vol. 119, no. 1-3, pp. 133-139, 2001.

[3] Iwata, K. and Moriwaki, T., "An application of acoustic emission to in-process sensing of tool wear", *Annals of the CIRP*, vol. 26, no. 1-2, pp. 21-26, 1977.

[4] Stein, J. L. and Huh, K., "A Design Procedure for Model-Based Monitoring Systems: Cutting Force Estimation as a Case Study", *Control of Manufacturing Processes, ASME*, vol. 28, no. 45–5, 1991.

[5] Li, X. and Yuan, Z., "Tool wear monitoring with wavelet packet transform- fuzzy clustering method", *Wear*, vol. 219, no. 2, pp. 145–154, 1998.

[6] Lim, S.C., Lim, C.Y.H., "Effective use of coated tools - the wear-map approach". *Surface and Coatings Technology*, vol. 139, no. 2-3, pp. 127-134, 2001.

[7] Mohd Zaki, N., Jaharah, A. G., Mohd Jailani, M. N., "Determination of machine tool wear using Ikaz method". *Proc. of Advanced Process and System in Manufacturing*, UKM Bangi, Selangor, pp. 71-79, 2005. (In Malay)

[8] Bandes, A. S., *Ultrasonics: Industry's Multipurpose Maintenance Technology, Sensor Technology and Design*. UE Systems, Inc., Elmsford, NY. 2003.

[9] Nuawi M.Z., Nor M.J.M., Jamaludin N., Abdullah S., Lamin F. and Nizwan C.K.E., "Development of Integrated Kurtosis-Based Algorithm for Z-Filter Technique". *Journal of Applied Sciences*, vol. 8, no. 8, pp. 1541-1547, 2008.

[10] Dawson, T. G., Kurfess, T. R.," Modelling the progression of flank wear on uncoated and ceramic-coated polycrystalline Cubic Boron Nitride tools in hard turning". *Journal of Manufacturing Science and Technology*, vol. 128, no. 1, pp. 104-109, 2006.

[11] Che Haron, C. H., Ginting, A., Goh, J. H., "Tool life and surface integrity in turning titanium alloy", *Journal of Materials and Processing Technology*, vol. 118, no. 1-3, pp. 231-237, 2001.

[12] Ezugwu, E. O., Bonney, J., Yamane, Y., "An overview of the machinability of aeroengine alloys", *Journal of Materials and Processing Technology*, vol. 134, no. 2, pp. 233-253, 2003.

[13] Tipnis, V. A., Peterson, M. B., Winer, W.O., *Wear Control Handbook*, American Society of Mechanical Engineers, New York, 1980.