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Mathematical Models of Flank Wear Using Vibration Amplitude Ratio in Drilling

This paper presents a model for on-line prediction of a drill flank wear using changes in vibration amplitude in the drilling process. Prediction of wear-time and wear-amplitude ratio relationships during the drilling process is enabled by this mathematical model through variations in vibration amplitude signals. An empirical method for an in-process approach for quantifying tool wear, and failure following it, is the outcome of the measurement of variations in the ratio of amplitude between torsional-axial dominant first mode (T_{P1}) and the second mode (T_{P2}) frequency. Performance of a series of cutting tests has been undertaken to study the effect of drill flank wear and other independent cutting parameters on the vibration amplitude signals. The objective is extended to finding the relationship between amplitude signals, drill flank wear and various other independent parameters. Details of the flank wear of drill and the ratio of amplitudes seen at various working conditions were determined and collected through experimental procedures. Verification of the model was done through comparison of the experimental values with the predicted values.

Keyword : *Tool wear Monitoring, Flank wear, Drilling Process, Vibration, Torsional-axial vibration.*

1. INTRODUCTION

Developments of robust and empirical methods are imperative for the development of a fully automated machining system. Such methods are meant to sense tool wear and the cutting area that is not easily visible during drilling which render monitoring of the process even more difficult [1]. Of late, tool changing criteria are based on a conservative estimation of tool life. In these methods, there are two possible ways of utilizing the tools that affect the machining process:

- Underutilization of a tool which results in frequent tool change and a longer machine down time, thereby reducing the system productivity and an increase of cost.
- Overutilization of a tool which affects the workpiece quality, surface finish and dimensions and disrupts the automated machining operation.

Therefore, Tool Condition Monitoring Systems (TCMS) are imperative for the measurement of the progress of tool wear using sensors during the cutting operation to enable timely replacement of the worn-out tool so that tool utilization can be more effective and to enhance machine tool automation. TCM systems can be widely categorized into two methods [2].

- Off-line monitoring methods that provide actual tool wear measurement through removal of the tool after machine being stopped.
- On-line monitoring methods that provide a measurement of parameters that have a correlation with tool wear..

Lee et al, [3] have reported the observation of force and vibration acceleration signals in the feed direction as highly significant due to the increase in amplitude level. Lim [4] concludes that vibration signature ana–lysis is a promising method for in-process monitoring of tool flank wear detection. Tool wear measurement is established by regarding tool life as a function of vibration amplitude. A unique model for on-line prediction of the tool flank wear in turning with use of the spindle speed change was established. It proved that prediction from the model gives good agreement with flank wear measurements [5]. Bergstorm et al, [6] have suggested that the cast bars used for the drilling tests and the tubes turned for calibration are from two different sources. This leads to microstructure variations and gives a solution with an incorrect coefficient during the development of mathematical model.

There have been a number of attempts to develop mathematical models that describe wear-time and wear-force relationships. Cutting force components are seen in good agreement and also a practical method to an in-pro–cess approach to help quantifying tool wear and fai–lure [7]. Popovic et al, [8] have quantified total forces based on the tool geometry by adding all discretized cutting edges. The authors have conducted experiments without any coolant and also suggested that special retro–fitting required for holding dynamometer on CNC turret lathe. Shin et al, [9] have suggested indirect cutting force mea–surement through use of acceleration sensor and current

Received: Sep 2018, Accepted: March 2019
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doi: 10.5937/fmet1903430N

hall sensor frequency analysis for micro and milling process. Based on the results reported, they conclude that the predictions that are achieved by calculations had better linearity using an acceleration sensor compared to a current hall sensor. Choudhury and Kishore [10] have developed an improved regression model for on-line monitoring of tool flank wear in the turning process. Favorable comparisons with experimental results have been achieved in the establishment of relationship bet–ween the components of force ratio and tool flank wear.

This work brings a mathematical model for drill flank wear as function of vibration amplitude ratio, cutting spe-ed, feed rate, and depth of cut, all being established through use of experimental data. Verifi–cation of the model has been accomplished through a series of validation tests.

2. THE MODEL FORMULATION

The drill wear can be categorized mainly as flank wear and crater wear. The portion worn behind the cutting edge on the flank surface of the drill tool is "flank wear". This is shown in Figure 1, [11] .

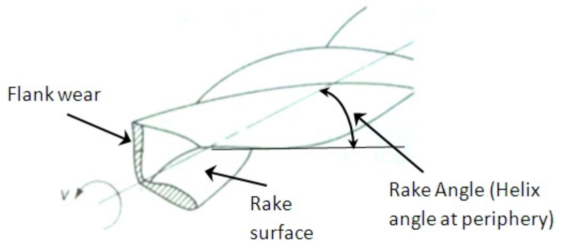

Figure 1. Drill flank wear

This type of wear is in existence during the contact of the flank face with the workpiece in drilling and arises out of friction between the clearance surface of the contact area of drill and the workpiece. This leads to a gradual increase in drill wear. This is considered as a good measure of observation of the severity of drill wear by most of the researchers [12-21]. Crater wear occurs at a high temperature condition along the rake surface.

This causes a drill bit to change the mechanics of the cutting process which is the result of changes occurring in effective rake angle and chip-cutting tool contact length, which weakens the tool in the process. Flank wear results in the drill bit changing the drilling process mechanics, an increase in chatter and a poor surface finish of the product. This explains the attention paid by most of the researchers to flank wear and hence the model formulation for drill flank wear analysis is developed.

The group of 27 experiments performed under different cutting conditions is presented in Table 1. Development of mathematical models with the use of multiple regression analysis (which make use of the least square method) has been possible with these data. Friedman and Field [22] have suggested the possibility of extending Taylor's equation for the relationship between cutting tool life T and cutting independent process variables: cutting speed (v), feed rate (f), and depth of cut (d) which can be written in the form of:

$$T = \beta_0 v^{p1} f^{p2} d^{p3} \tag{1}$$

Table 1. Experimental data on Amplitude Ratio and Flank wear

Experiment Number	Cutting speed (rev/min)	Feed rate (mm/rev)	Depth of cut (mm)	Amplitude Ratio	Flank wear (mm)		Error %
					Measured (mm)	Calculated (mm)	
1*	800	0.089	9	18.2	0.22	0.2185	0.67
2*	800	0.089	11	34.6	0.32	0.3165	1.1
3	800	0.089	14	40.4	0.36	0.3471	3.6
4	800	0.125	9	13.2	0.21	0.1832	12.8
5*	800	0.125	11	17.5	0.276	0.2160	21.75
6*	800	0.125	14	23.2	0.32	0.2550	20.33
7*	800	0.15	9	10.7	0.21	0.1635	22.14
8	800	0.15	11	15.4	0.256	0.2019	21.11
9	800	0.15	14	13.6	0.292	0.1903	34.84
10*	900	0.089	9	13.9	0.240	0.1878	21.73
11*	900	0.089	11	39.1	0.364	0.3400	6.59
12*	900	0.089	14	47.3	0.487	0.3805	21.87
13*	900	0.125	9	13.7	0.232	0.1877	19.1
14	900	0.125	11	32.4	0.344	0.3071	10.73
15	900	0.125	14	48.4	0.461	0.3877	15.89
16	900	0.15	9	15.5	0.256	0.2022	21.02
17*	900	0.15	11	25.6	0.333	0.2698	18.96
18*	900	0.15	14	44.6	0.445	0.3716	16.48
19*	1000	0.089	9	15.9	0.244	0.2032	16.70
20*	1000	0.089	11	38.7	0.36	0.3386	5.94
21	1000	0.089	14	48.6	0.46	0.3872	15.82
22	1000	0.125	9	11.8	0.22	0.1732	21.27
23*	1000	0.125	11	26.3	0.34	0.2736	19.52
24*	1000	0.125	14	43.3	0.444	0.3651	17.78
25	1000	0.15	9	9.2	0.222	0.1518	31.63
26*	1000	0.15	11	11.4	0.268	0.1726	35.61
27*	1000	0.15	14	39.4	0.430	0.3478	19.12
Average Error %							17.56

where β_o is a coefficient and p_1, p_2 and p_3 are constants that depend on the mechanical properties of the material being machined.

Development of the wear on the flank is pro–portional to the area of flank wear scar at time t can be expressed as [23]

$$W = W_0 + \Delta W \qquad \text{or} \qquad W = W_0 + mt \tag{2}$$

where ΔW is the increase in wear, W_o is the initial wear, m is the slope of the wear-time curve and t is the cutting time. After a certain time of drilling, the increase of wear ΔW is independent on the individual cutting conditions given, the total wear can be given as [10],

$$W = W_0 + \beta_0 v^{p1} f^{p2} d^{p3} t^{p4}. \tag{3}$$

where v, f and d are the cutting speed, feed rate and depth of cut respectively.

Based on the experiments conducted by Nakandhrakumar et al. [24], the vibration amplitude with respect to the initial vibration amplitude before starting drilling and distance of measurement from sensor at time t can be expressed as:

$$A = A_0 + mt \tag{4}$$

where A_0 is the initial amplitude developed at time $t=0$ when there is no drilling, which is dependent entirely on the given cutting conditions, A is the amplitude after drilling at time (t) and m is the slope of the amplitude-time curve. This slope m is different at various values of cutting speed, feed rate and depth of cut. So Eq. (4) can be modified as

$$A = A_0 + \beta_1 v^{q1} f^{q2} d^{q3} \tag{5}$$

where A_o, q_1, q_2, and q_3 are constants which depend on the mechanical properties of the tool and material being machined. As drilling progresses, the drill flank sees a gradual wearing out, resulting in a continuous increase in vibration amplitude level. The conclusion, therefore, is that the feasibility of estimation of the variations in drill flank wear through measurement of variations in vibration amplitude. The dependence of the initially developed amplitude and the initial drill flank wear is mainly on cutting conditions measured as speed, feed rate and depth of cut. Hence, the vibration amplitude and the drill flank wear can be written as

$$W = \beta_0 A^{p1} + \beta_1 v^{q1} f^{q2} d^{q3} \tag{6}$$

The dominant first mode peak amplitude (T_{P1}) arising as a result of torsional-axial frequency vibration [24-26] increases gradually at the instant of tool wears while the corresponding dominant second mode peak amplitude (T_{P2}) of the same gives the impression of being most sensitive to machining instability. The two amplitudes at different frequency at the first mode peak, (T_{P1}), and the second mode peak, (T_{P2}), appear to indicate the condition of the drill totally. So it is logical to state that these two amplitudes could be used for predicting the value of drill flank wear at any point of time. The ratio of the dominant peak to the second peak ie., T_{P1}/T_{P2} has been considered as a parameter, for the purpose of incorporating these amplitudes into the proposed mathematical model. The introduction of the ratio T_{P1}/T_{P2} nullifies the effects of process variables and amplitude variation due to sensor position. So the drill flank wear can be finally expressed as:

$$W = \beta_0 \left(\frac{T_{p1}}{T_{p2}} \right)^{p1} + \beta_1 v^{q1} f^{q2} d^{q3} \tag{7}$$

where T_{P1} and T_{P2} are vibration amplitude of the first and the second mode peaks of torsional-axial frequency, v is the cutting speed of the machine (rev/min), f is the feed rate (mm/rev), d is the depth of cut (mm), and β_0, β_1, q_1, q_2, and q_3 are constants of the equation to be determined from the experiments.

Solution to the regression model derived for the above Eq. (7) has been provided for estimating the un–known constants. The method of least squares was adopted for this purpose.

3. EXPERIMENTAL SET-UP AND MEASUREMENT RESULTS

The schematic representation of experimental set-up is illustrated in Figure 2 (a). Figure 2(b) and 2(c) show the sensor position which is placed at the centre of the plate which has been shown in front view and top view respectively. Drilling tests were carried on a 3 HP, HAAS machine without coolant using High Speed Steel (HSS) tools with IS 5101-1991 tool geometry. Five workpieces of EN24 steel, 120 mm in diameter and 9 mm in thickness were used. The samples were maintained with the hardness of 30.9 HRC. An accelerometer sensor was mounted at the centre of the workpiece ie. at 60mm from the holes that are to be machined, to measure the acce–leration due to vibration [24]. This particular drill bit /workpiece combination and machine capability, as per ASM Handbook [28] has been investigated through experiments carried out in different cutting conditions in the range that follows: Spindle speed: 800- 1000 rev/min; Feed rate: 0.081 to 0.12 mm/rev; Depth of cut: 9 to 14 mm;

A Taguchi factorial design procedure was used to reduce the number of experiments required. Implemen–tation of a three-level factorial design for three factors has been taken up [29]. The individual cutting para–meters considered were cutting speed, feed rate and depth of cut. So the 3^3 factorial designs were imp–lemented. Decision on the three levels of all factors was taken on the basis indicated in handbooks, machine capability, and past experience. The total number of experiments was 27. Data acquisition card (NI 9233) was also connected thro-ugh side connector of sensor at the one end and the other end was connected to the Laptop for signal processing using LabVIEW software. The processing was carried out in the Fast Fourier Transform (FFT) analyzer for analysis. Drill bit was removed after each test for flank wear measurement. Measurement of drill flank wear was done using a tool maker's microscope(Siphon TM; Model No. 176-811E). Then it was refitted for further drilling ope-ration. Tests were stopped when the drill flank wear had surpassed the wear limit or when objectionable factors such as excessive vibration were noticed.

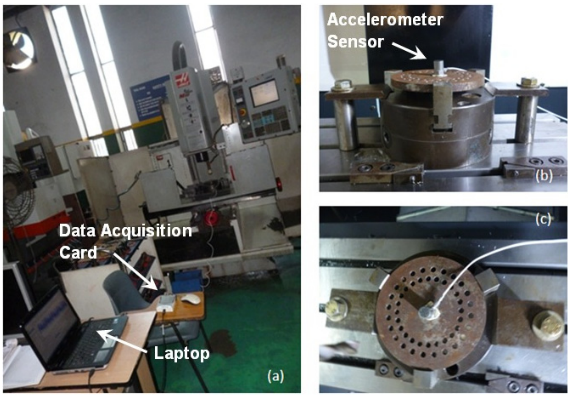

Figure 2: a) Illustration of Experimental set-up for vibration measurement; b) Front view; c) Top view of sensor position

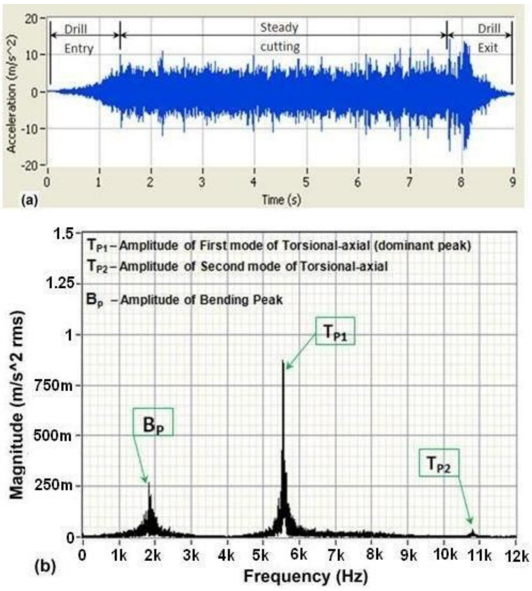

Figure 3: Examples of acceleration signal acquired by accelerometer: (a) in time domain; (b) corresponding FFT spectrum

Figure 3 (a) and (b) indicate the results from in time trace and corresponding FFT spectrum respectively. Experimental results presented by Roukema and Altindas [25] indicate dominance of torsional-axial mode peak. Arvajeh and Ismail [26] have categorized the FFT spectrum peaks obtained during drilling. The dominant peak is referred to as torsional-axial of 1st mode due to instability ie. marked as T_{P1} and torsional–axial of 2nd mode during exit of drilling ie. marked as T_{P2}. B_P is the Bending peak frequency occurs as a consequence of rotational speed and it appears as twice the frequency due to bending of drill bit in both the directions.

Imani and Moosavi [27] have confirmed the possibility of seeing FFT spectrum of amplitude data as two strong peaks at frequency around 2000 Hz (lateral frequency) and at the frequency around 5900 Hz (axial frequency) for 6 mm drill during drilling. Only T_{P1} and T_{P2} are considered in this work for development of a regression model for predicting drill flank wear as contribution of B_P has very low significance in drill flank wear.

4. RESULTS AND DISCUSSION

A multiple regression model Eq. (7) with linear polynomial of the first order has been developed. Application of Multiple linear regression techniques is made for estimating the model parameters or model coefficients (β_o and β_1). Randomly 17 experiments out of 27 experiments of Table 1 are used for finding coefficients of β_o and β_1. The Multiple linear regression coefficients can be found by the following equation (Krishnaiah and Shahabudeen, 2012)

$$\hat{\beta} = \left[X^T X \right]^{-1} X^T Y \tag{8}$$

where, X is the average of all input variables and Y is the output variable. $\hat{\beta}$ is the coefficients of individual parameters ie. β_o and β_1.

The final mathematical multiple regression equation of vibration amplitude ratio-wear characteristics was

$$W = 0.04\left(\frac{T_{p1}}{T_{p2}}\right)^{0.58} + 0.0000016 v^{1.13} f^{0.92} d^{1.052} \tag{9}$$

The model has been programmed in MATLAB 14.0 to find the drill flank wear. The input values of the parameters such as amplitude ratio, cutting speed, feed rate and depth of cut were provided to the equation and the output variable drill flank wear was predicted for all 27 experiments. Figure 4 shows that the scatter graph has been drawn for the measured and predicted drill flank wear for the remaining 10 experiments. It can be seen that there is a good agreement between the two set of data on flank wear calculated and measured. The average percentage error is approximately 17.56%, indicating the closeness of values for all the 10 expe–riments. The error % between the measured and pre–dicted drill flank wear is found using the ratio of the difference between the measured to the predicted drill flank wear to the measured flank wear. It is given mathematically by

$$Error\% = \left| \frac{m-p}{p} \right| * 100 \tag{10}$$

where m is the measured flank wear values in mm, p is the predicted flank wear values through theoretical model in mm.

The variation in value among the process parameters is analyzed through regression analysis which gives the coefficient of correlation between the measured and predicted flank wear values and found to be 0.8244. Thus, the reliability of developed multiple regression model to predict the drill flank wear values for certain range of input parameters is as high as 82.44%.

4.1 Effect of individual parameters on drill flank wear

Investigation of the influence of various individual parameters on the drill flank wear such as amplitude ratio, cutting speed, feed rate and depth of cut are investigated. The influence of each parameter is assessed through test by keeping all other factors constant and changing one variable within range at which flank wear is also minimum.

Figure 5(a) shows the condition of the experiments with different feed rate effects on flank wear while drilling by cutting speed = 800 rpm, depth of cut = 9 mm, distance from sensor = 60 mm, amplitude ratio = 13.2. Drill flank wear values caused by vibration signal increase with the increase in feed. This is due to the resistance which is the result of friction at the drill and workpiece interface increase with increase in drill wear, which in turn increases the magnitude of vibration signal. This is done in calculation after obtaining the reduced equation. The flank wear values are calculated over a range of values of input individual parameter. The other plots are shown in Figure 5(b) – 5(d). These plots are also drawn between the flank wear and the individual parameters. Some other plots such as relationship between flank wear and depth of cut, flank wear and cutting speed, and flank wear and amplitude ratio.

In an earlier publication, Nakandhrakumar et al., [24] have established the relationship between distance variation of drilling holes from position of sensor and RMS-amplitude of the vibration signal of 1st hole data (all PCDs) through experiments. It is obvious the postion of sensor as a highly influencing factor in the vibration measurements. The authors conclude that introduction of a novel procedure nullifies variation of amplitude level occurring arising from distance variation from sensor positioning. So, the amplitude is insensitive to the distance of sensor, but it is sensitive to the wear progression.

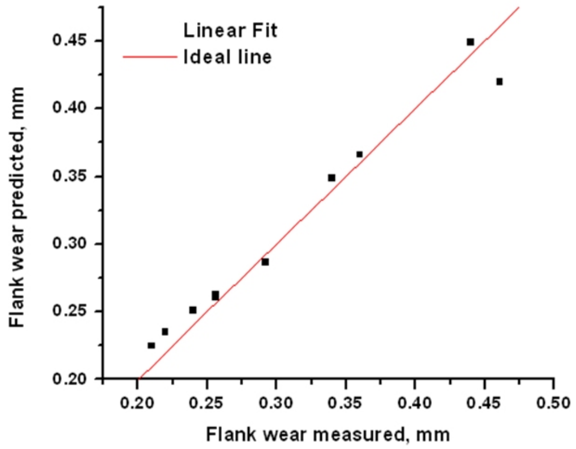

Figure 4: Relationship between the flank wear measured and predicted

The line graph illustrates the flank wear in mm from 0.2mm to 0.5mm for the different cutting parameters such as feed rate, depth of cut, cutting speed and amplitude ratio at different cutting conditions. Overall, it can be seen that flank wear was far higher during the cutting speed changes compared to the other three individual parameters throughout the whole machining conditions. To begin, increases of flank wear by the parameters feed rate, depth of cut and amplitude ratio followed a fairly similar linear pattern for the change in cutting conditions from 0.08 to 0.12 mm/rev, 9 to 14 mm and 13.2 to 14.2 respectively. In this case an equation of Eq. (11) was attained with the power of 'e' approaching unity. Hence the following linear equation was obtained [10]:

$$Y = mx^{e} + C \tag{11}$$

Figure 5 (a), 5(b) and 5 (d) show the relationships for these parameters with flank wear.

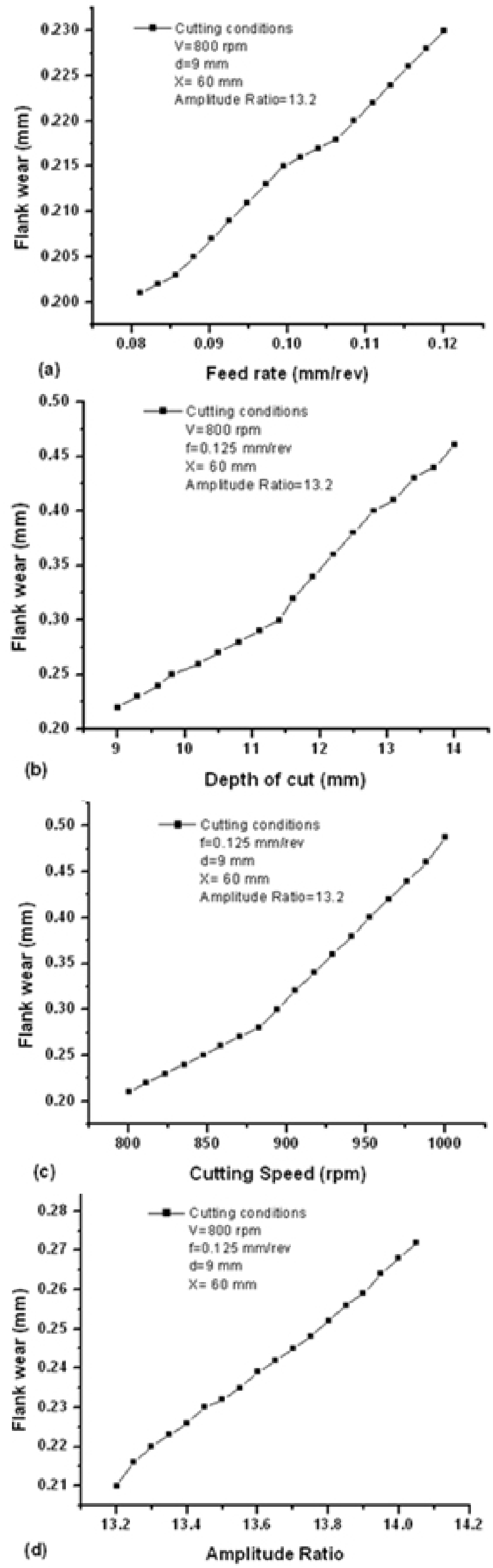

Figure 5: Plots of relationship between the drill flank wear and (a) feed rate, (b) depth of cut, (c) cutting speed, and (d) amplitude ratio

Figure 5 (c) shows the relationships for cutting speed of 800 to 1000 rpm with flank wear. Interestingly in this case, the parabolic equation was attained with the power of 'e' as 1.13. This parameter is the most influential, among all other parameter affecting flank wear. This reiterates the conclusion seen in literature [10, 20]. The parameter amplitude ratio is also affecting the tool wear significantly. Hence, this can be reliable one to use for monitoring progression of tool wear.

5. CONCLUSION

The developed mathematical model of the wear-time-independent parameter relationships is found to be more reliable for estimating drill flank wear. The variation of vibration amplitude during drilling that has been discovered not only correlates well with drill flank wear height on the flank face but is also sensitive to disturbances slightly seen during machining. Each of the torsional-axial dominant first (T_{P1}) and second (T_{P2}) mode peak amplitudes are observed as highly sensitive to the progression of drill flank wear and failure. Drill flank wear has been arrived at indirectly through measurement of measurable quantity such as the ratio of T_{P1} to T_{P2}. Following are the conclusions.

- For drill flank wear monitoring, correlation of mathematical model between the T_{P1} to T_{P2} and the drill flank wear dimension measured in height has been accomplished successfully.
- Prediction of drill flank wear from the model correlate well with actual flank wear measurement.
- The influence of different independent parameters on drill flank wear was examined using the developed mathematical model and experimental results. Increase in drill flank wear was linear with the feed rate, amplitude ratio and depth of cut. The vibration amplitude ratio T_{P1}/T_{P2} is a good indicator to predict and monitor the drill flank wear.

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NOMENCLATURE

A_0	Amplitude developed at distance X=0 when there is no drilling
A	Amplitude after drilling at distance X from sensor
D	Depth of cut, mm
F	Feed rate, mm/rev
FFT	Fast Fourier Transform
HSS	High Speed Steel
T	Tool life
$TCMS$	Tool Condition Monitoring Systems
T_{P1}	Amplitude of torsional-axial dominant first mode peak, m/s^2
T_{P2}	Amplitude of torsional-axial dominant second mode peak, m/s^2
V	Cutting speed, rev/min
W	Flank wear, mm
ΔW	Increase in wear, mm
W_0	Initial wear, mm
X	Distance from the position of sensor, mm

МАТЕМАТИЧКИ МОДЕЛИ ХАБАЊА БОЧНЕ ПОВРШИНЕ АЛАТА КОРИШЋЕЊЕМ ОДНОСА АМПЛИТУДА ВИБРАЦИЈА КОД ОБРАДЕ БУШЕЊЕМ

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Приказан је модел за онлајн предикцију хабања бочне површине бушилице коришћењем промена у амплитудама вибрација код обраде бушењем. Предикција повезаности времена хабања и односа хабање-амплитуда у процесу бушења је омогућено математичким моделом кроз варијације сигнала амплитуда вибрација. Емпиријски метод за директан приступ процесу у циљу квантификације хабања алата и његовог отказа је резултат мерења варијација у односу вибрација између фреквенција торзионо-аксијалног првог режима (T_{p1}) и другог режима (T_{p2}). Серијом тестова је испитан утицај хабања бочне површине алата и других независних параметара резања на сигнале амплитуда вибрација. Циљ истраживања је проширен утврђивањем односа између сигнала амплитуда, хабања бочне површине алата и различитих других независних параметара. Појединости хабања и однос амплитуда су одређене у различитим радним условима и прикупљене кроз експерименталне поступке. Верификација модела је извршена упоређивањем експерименталних и вредности утврђених предикцијом.