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Estimation of Tool Wear Rate in Orthogonal Cutting Using Experimental and Statistical Approach

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ABSTRACT

This study presents a new methodology to estimate tool wear rate in orthogonal cutting based on experimental data and statistical approach. In metal cutting tool wear is strongly influenced by cutting forces, speed, feed, and depth of cut. Based on these variables and cutting forces measured by dynamometer, tool wear is estimated with desired accuracy. The major objective of this study is to develop a model (equation) to predict the tool wear in orthogonal cutting by regression analysis. The work presented in this paper uses the data of conducted experiments. This data is statistically analyzed to develop a model, which can predict the wear rate of cutting tool used in orthogonal cutting operation considering different machining variables such as, spindle speed, depth of cut, feed. The cutting forces predicted by the regression analysis equation (model) is closely matching with those with results obtained experimentally. So based on another statistical equation tool wear rate is estimated over the wide range of speed, feed and depth of cut values required for different types of machining operations. The proposed methodology can be used for developing another model which will predict the tool wear rate for other machining processes.
Keywords: Regression Analysis, Wear Rate, Kurtosis-based Algorithm, 3D Graphic, Geometric Tolerance

I. INTRODUCTION

Tool wear is defined as change of shape of the tool from its original shape, during cutting, resulting from the gradual loss of tool material. Cutting tools are subjected to an extremely severe rubbing process. They 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 (finish). However, wear occurs during the cutting action, and it will ultimately result 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 guarantee the desired cutting action. Tool wear has a large influence on the economics of the machining operations. Thus, knowledge of tool wear mechanisms and capability of predicting tool life are important and necessary in metal cutting. A view of the functional elements that affect the wear of a cutting tool is illustrated in Fig. 1

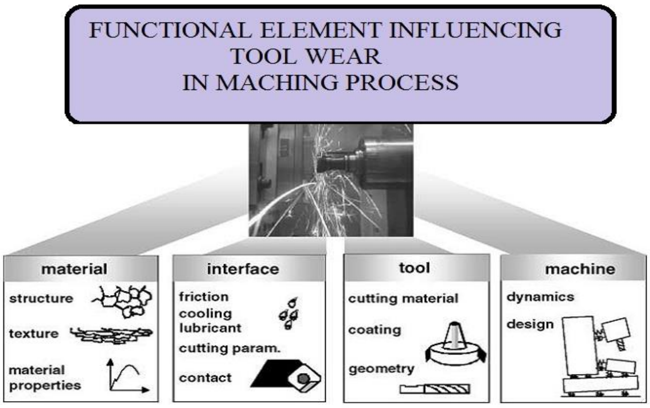

Figure 1: Elements Affecting Tool Wear

The high contact stress between the tool rake-face and the chip causes severe friction at the rake face, as well, there is 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 as shown in fig. 2.

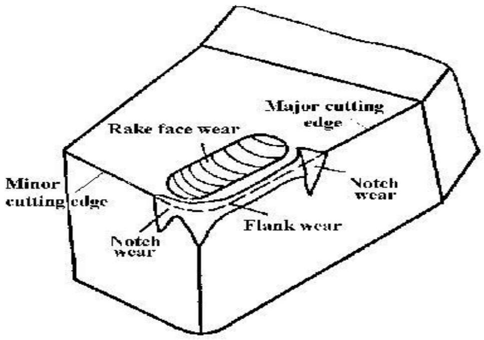

Figure 2: Rack Face and Flank Face

Literature Review

In this chapter an overview of different literatures in this context is given. Ghani et. al. [1] , presented 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. Huang, et. al. [2] studied two major approaches using sensing technology for detecting tool breakage: one is the direct method, which measures and evaluates the volumetric change in the tool, and the other is the indirect method, which measures the cutting parameters during the operation process. The indirect method can work as an on-line technique because it measures the cutting parameters during the operation process. To detect the tool breakage immediately, the indirect sensing technology is recommended. Tyan et. al.[3] the orthogonal metal cutting process for a controlled contact tool is simulated using a limit analysis theorem. The basic principles are stated in the form of a primal optimization problem with an objective function subjected to constraints of the equilibrium equation, its static boundary conditions and a constitutive inequality. Mustafa et, al. [4] presented the geometric tolerance and surface quality of an aluminium piece produced by turning is analysed. The effect of the length and diameter of working piece, cutting depth and feed were also investigated. The cutting speed, which is an important machining parameter, was kept constant in this study. Astakhov et, al,[5] conducted experimental study to assessment and proper reporting of the tool wear rates. Duan et. al, [6] presented in their study the prediction of chip morphology. As an advanced manufacturing technology which has been developed rapidly in recent years, high speed machining is widely applied in many industries. The chip formation during high speed machining is a complicated material deformation and removing process. Senussi et al.[7] presented the effect of turning process parameters (cutting speed, feed rate, and depth of cut) and distance from the center of work piece as input variables on the chip micro-hardness as response or output. Rumah et, al, [8] presented an experimental investigation of the influence of the three most important machining parameters of depth of cut, feed rate and spindle speed on surface roughness during turning of mild steel. In this study, the design of experiment which is a powerful tool for experimental design is used to optimize the machining parameters for effective machining of the workpiece.

II. METHODS AND MATERIAL

A. Regression Analysis

Regression analysis is the statistical technique that identifies the relationship between two or more quantitative variables: a dependent variable whose value is to be predicted, and an independent variable about which knowledge is available. The technique is used to find the equation that represents the relationship between the variables. A simple regression analysis can show that the relation between an independent variable X and a dependent variable Y is linear, using the simple linear regression equation Y=b0 + b1X (where a and b are constants). Multiple regression will provide an equation that predicts one variable from two or more independent variables, Y = b0 + b1X1 + b2X2 + b3X3…..bkXk.

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B. Multiple Regression Analysis

Multiple regression is a methodology for studying relationships between variables. It is implemented to determine the relationship between independent and dependent variables and may be used to analyze data and generate a model. From multiple regression model, one can obtain the predictive variables and determine the relationship between the criterion variable and the predictive variable. Therefore multiple regression will be useful when predicting the dependent variable such as maximum cutting force of each revolution via independent variables such as spindle speed, feed rate, and depth of cut. Let the depedent variable of intrest be y which depends on two independent variables, say x1, x2 and x3. The linear relationship, among y , x1, x2, and x3 can be expressed in the form of the regression equation of y on x1, x2, and x3, in the following form:

Y = b0 + b1X1 + b2X2 + b3X3

Where b0 is referred to as 'intercept' and b1, b2, & b3 are known as regression coefficients. The effectiveness or the reliability of the relationship thus obtained is judged by the multiple coefficient of determination, usually denoted by R2 , and is defined as the ratio of variation explained by the regression equation and total variation of the dependent variable y. Thus,

R2 = [Explained Variation in y / Total variation in y]

R2= 1-(Unexplained variation÷Total Variation)

R2= 1-[Σ (yi-ŷi)2]/[Σ (yi-ȳi)2]

The total variation in the variable y is equal to the variation explained by the regression equation plus unexplained variation by the regression equation. Mathematically, this is expressed as,

Total Variation($\Sigma (y_i-\bar{y}_i)^2$) = Explained Variation($\Sigma(\hat{y}_i-\bar{y}_i)^2$) + Unexplained Variation ($\Sigma(y_i-\hat{y}_i)^2$)

Where yi is observed value of y, ȳ is the mean of all yi,, ŷ is the estimate of the value yi by the regression equation. R is known as the coefficient of multiple correlations, and is always between 0 and 1. In fact, R is the correlation between the dependent variable and its estimate derived from multiple regression equation and as such it has to be positive. [21]

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Table 1. Experimental Data

Obs. No.	Vc, (m/min)	F, (mm/rev)	Doc, (mm)	Fa,(N)	Fr, (N)	Ft, (N)
1	90	0.08	0.15	30.25	89.67	70.67
2	90	0.08	0.3	66.75	139.2	130.8
3	90	0.12	0.15	32.71	100.4	80.4
4	90	0.12	0.3	85.64	157.5	146.4
5	90	0.16	0.15	35.03	115.9	107.1

6	90	0.16	0.3	90.32	174.4	176.9
7	120	0.08	0.15	29.34	83.21	58.59
8	120	0.08	0.3	66.27	134.2	124.9
9	120	0.12	0.15	32.69	93.22	79.61
10	120	0.12	0.3	74.64	142.6	136.1
11	120	0.16	0.15	34.13	104.9	96.02
12	120	0.16	0.3	76.13	161.9	169.6
13	180	0.08	0.15	27.68	70.57	50.58
14	180	0.08	0.3	64.05	120.9	105.8
15	180	0.12	0.15	29.24	92.3	64.74
16	180	0.12	0.3	66.33	127.2	117.0

The linear relationship, among y, X1, X2, and X3 can be expressed in the form of the regression equation of y on X1, X2, and X3, in the following form:

For Fa: $y=-14.8725-0.08133\times X1+121.20\times X2+283.55\times X3$

For Fr: $y=30.485-0.21833\times X1+342.075\times X2+339.90\times X3$

For Ft: $y=-9.7868-0.270\times X1+121.20\times X2+416.03\times X3$

This equation is known as multiple regression equation of y on X1, X2, and X3, and it indicates as to how y changes with respect to changes in X1, X2, and X3.

The effectiveness or the reliability of this relationship is judged by the multiple coefficient of deformation, usually denoted by R2, and is defined as:

TABLE 2: Predicted Force &Variation for Fa

Obs. No.	**Acutal Force**	**Predicted force**		**Unexplained variation**	**Total variation**
	y_i	$\hat{y}_i$	$y_i-\hat{y}_i$	$(y_i-\hat{y}_i)^2$	$(y_i-\bar{y}_i)^2$
1	30.25	29.8865	0.36	0.13	498.40
2	66.75	72.269	-5.5	30.45	4455.56
3	32.71	34.7347	-2.02	4.099	1069.94
4	85.64	77.1172	8.52	72.63	7334.20
5	35.03	39.583	-4.553	20.72	1227.10
6	90.32	81.9655	8.35	69.79	8157.70
7	29.34	27.4466	1.89	3.5849	860.83
8	66.27	69.8291	-3.5	12.66719	4391.71
9	32.69	32.2948	0.39	0.156183	1068.6
10	74.64	74.6773	-0.03	0.001391	5571.12
11	34.13	37.143	-3.01	9.0781	1164.85
12	76.13	79.5255	-3.39	11.529	5795.77
13	27.68	22.5666	5.11	26.146	766.18
14	64.05	64.9491	-0.89	0.8083	4102.40

15	29.24	27.4148	1.82	3.3313	854.97
16	66.33	69.7973	-3.46	12.02216	4399.66
Sum	**841.2**	**841.2**		**277.182**	**51719.10**
Mean	52.575				

For Fa:-

R^2= 1-(Unexplained variation÷Total Variation)

R^2= 1-[Σ (yi-ŷi)2]/[Σ (yi-ȳi)2]

R^2= 1-[277.1826/ 51441.92]

R^2= 0.994641

TABLE 3: Predicted Force Vs Actual Force Fr

Obs No.	Acutal Force	Predicted force		Unexplained variation	Total variation
	y_i	$\hat{y}_i$	$y_i-\hat{y}_i$	$(y_i-\hat{y}_i)^2$	$(y_i-\bar{y}_i)^2$
1	89.67	89.188	0.482	0.232324	877.08
2	139.24	140.175	-0.935	0.874225	19387.7
3	100.45	102.87	-2.42	5.8564	10090.20
4	157.54	153.858	3.682	13.557124	24818.85
5	115.96	116.554	-0.594	0.352836	13446.72
6	174.44	167.54	6.9	47.61	30429.31
7	83.21	82.633	0.577	0.3329	6923.90
8	134.27	133.62	0.65	0.4225	18028.4
9	93.22	96.321	-3.101	9.6162	8689.96
10	142.64	147.301	-4.661	21.7249	20346.16
11	104.96	110.005	-5.045	25.4520	11016.6
12	161.92	160.99	0.93	0.8649	26218.08
13	70.57	69.53	1.04	1.0816	4980.12
14	120.92	120.52	0.4	0.16	14621.64
15	92.3	83.22	9.08	82.4464	8519.29
16	127.26	134.208	-6.948	48.274704	16195.1076
Sum	**1908.57**	**1908.533**		**258.859089**	**234589.284**
Mean	119.285				

For Fr:-

R^2= 1-(Unexplained variation÷Total Variation)

R^2= 1-[Σ (yi-ŷi)2]/[Σ (yi-ȳi)2]

R^2= 1-[258.8591/ 234589.3]

R^2= 0.998897

TABLE 4: Predicted Force &Variation for Ft

Obs No.	Acutal Force	Predicted force		Unexplained variation	Total variation
	y_i	$\hat{y}_i$	y_i-$\hat{y}_i$	$(y_i-\hat{y}_i)^2$	$(y_i-\bar{y}_i)^2$
1	70.67	67.83	2.84	8.0656	1336.17
2	130.84	130.35	0.49	0.2401	17119.10
3	80.4	87.55	-7.15	51.1225	6464.16
4	146.43	150.075	-3.645	13.286025	21441.74
5	107.11	107.279	-0.169	0.028561	11472.55
6	176.97	169.79	7.18	51.5524	31318.38
7	58.59	59.72	-1.13	1.2769	3432.7881
8	124.9	122.24	2.68	7.1824	15605.0064
9	79.61	79.44	0.17	0.0289	6337.7521
10	136.1	141.96	-5.78	33.4084	18544.9924
11	96.02	99.16	-3.14	9.8596	9219.8404
12	169.6	161.68	7.93	62.8849	28767.5521
13	50.58	43.49	7.09	50.2681	2558.33
14	105.8	106.015	-0.165	0.027225	11204.22
15	64.74	63.21	1.53	2.3409	4191.26
16	117.0	125.73	-8.67	75.1689	13703.06
Sum	**1715.5**	**1715.519**		**366.7414**	**202716.92**
Mean	**107.2**				

For Ft:-

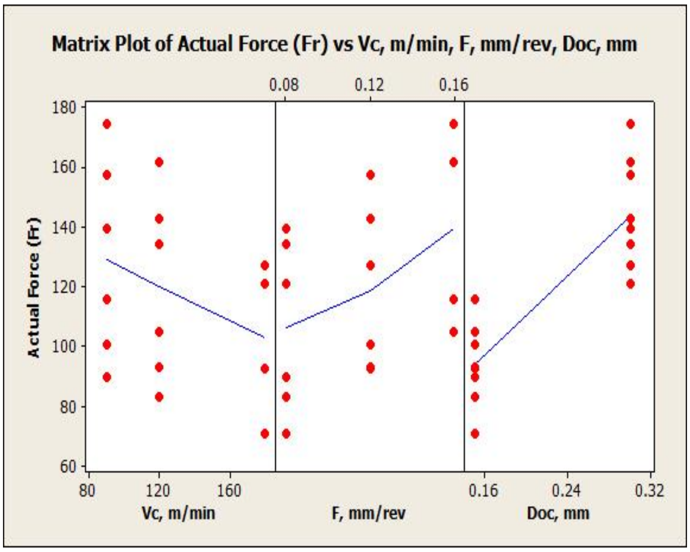
R^2= 1-(Unexplained variation÷Total Variation)

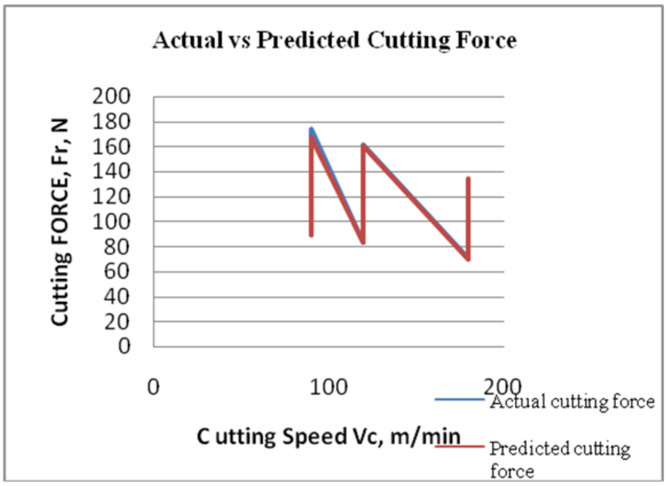
R^2= 1-[Σ (yi-ŷi)2]/[Σ (yi-ȳi)2]

R^2= 1-[366.7414 / 202350.2]

R^2= 0.998191

III. RESULTS





IV. CONCLUSION

The optimal performance of a cutting tool requires a correct combination of the cutting conditions such as cutting speed, feed rate, and depth of cut. The influence of depth of cut on cutting forces is more than speed and feed. The second factor affecting cutting force is feed rate. For cutting speed, its effect is less important. The results indicate that the lower cutting forces were generated at higher cutting speeds. Tool, and workpiece material as well as its physical properties, which determine cutting forces also plays an important role in tool wear during machining. Thus to get the good machining stability and better tool life, we must use higher cutting speed, moderate feed and lower depth of cut. Experimental and statically obtained results are same, hence we can conclude that statistical method is useful to estimate tool wear rate in machining.

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