DRILL WEAR MONITORING BY VIBRATION SIGNATURE ANALYSIS

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ABSTRACT

The useful life of a cutting tool and its operating conditions largely controls the economics of the machining operations. Hence, it is imperative that the condition of the cutting tool, particularly some indication as to when it requires changing, to be monitored. The largest amount of money spent on any one class of cutting tools is spent on drills. Monitoring of drills is an important task with a high degree of economical relevance; this is true especially for the use of twist drills, which are mostly used in a diameter spectrum between 1 mm to 20 mm. The paper deals with the comparative quality and performance analysis of the twist drills at different cutting condition as per the model, designed according to the factorial design method. Experiments were performed by using two twist drills of different make, possessing the same specifications. Drilling experiments with 14 mm drill size were performed at two cutting speeds and feeds. Selected values of controlling parameters (cutting speed, viscosity of lubricant, feed and number of holes) at each set of experiment shows their significant effect after regression analysis and is concluded along with the response parameters. Hardness values were measured for the drills at different locations and the conclusions are drawn by the frequency response analysis and surface roughness.

Keywords: Design of Experiment, Frequency Response, Regression Analysis, Surface Roughness, Twist Drills

1. INTRODUCTION

Machining operations such as turning, milling, drilling and grinding are material removal processes that have been widely used in manufacturing, since the industrial revolution. Of these processes, drilling is one of the most common machining operations in manufacturing. The drilling operation is also frequently used as a preliminary step for many operations like boring, tapping and reaming, however the operation itself is more complex and demanding [1].

Worn drills produce poor quality holes and in extreme cases a broken drill can destroy an almost finished part. A drill begins to wear as soon as it is placed into operation. As it wears, cutting forces will increases, the temperature of the drill rises and this accelerates the physical and chemical processes associated with drill wear and therefore drill wears faster. Different types of drill wear such as flank wear, crater wear and chisel edge wear and margin wear can be observed on drill because of the geometry of the drill and the cutting conditions vary along the cutting lips from the margin to the chisel edge. Drill wear is a progressive process which takes place at the outer margin of the flutes of the drill, due to an intimate contact with the work-piece as soon as it is placed into operation; however the wear occurs at an accelerated rate once a drill becomes dull. Direct measurements such as optical devices, lasers, proximity sensors which tend to be off-line techniques and indirect measurements in which cutting force, torque, current, vibration, acoustic emission are generally on-line techniques [2].

Vibration monitoring is of practical interest applicable in real time, as vibration is emerging as the most effective and versatile sensing medium for tool wear analysis. Matrin et al. [3] also sought a correlation between the vertical vibrations of a cutting tool and tool wear in turning operation, for which they found that the best vibration signals were achieved the nearer the accelerometer was placed to the point of contact between tool and work piece. Elwardany et al. [4] reported study on monitoring tool wear and failure in drilling using vibration signature analysis techniques, which are sensitive to drill wear and breakage in both time and frequency domains.

Ayesh *et al.* [5] have used vibration as one of the method of indirect method for drill tool wear analysis. They have developed a model to characterise the drilling process using wavelet analysis of the vibration signal collected from the process while cutting in order to detect wear. Thangaraj et al [6] have reported the use of vibration time domain analysis techniques for predicting drill breakage.

The aim of the present work is to identify suitable parameters, the monitoring of which will enable prediction of drill failure. To study the joint effect of the controlling factors on a response parameter of the tool, the mathematical model on the basis of factorial design is used and the experimentation was carried out accordingly for the twist drills of 14 mm diameter.

Table 1: Experimental conditions

No	Controlling parameters	Levels
a	Viscosity (lubricant)	0-33 cst and 1- 45.6 cst
b	Cutting speed	0 - 19.7 and 1 - 27.7 m/min
c	Number of holes	0 - 8 and 1 - 15 holes
d	Feed	0.937 to 1.31 and 1.5 to 2.1 mm/sec
e	Diameter 14 mm – X	Flute length – 108mm, overall –189mm
	Diameter 14 mm – Y	Flute length – 108mm, overall – 190mm

2. DESIGN OF EXPERIMENTS

A design of experiment with k factors each at two levels is considered for experimentation. The mathematical model on the basis of factorial design is formulated as 2k, where k = 4, such as cutting speed, feed, lubricant and number of holes.

Frequency responses are recorded at each experiment and the data collected above is used to establish the regression model. The functional relationship between the response parameters of the cutting operation and the integrated variables for the postulated model is obtained in the form of linear equation to interpolate the response by changing the values of controlling parameters. The various experimented parameters selected were shown in Table 1.

3. EXPERIMENTATION

Selection of work-piece material, size of work-piece and lubricating oil is adopted as per the testing conditions suggested by the manufacturer. The parameters that affect the quality and performance analysis like tool hardness; tool geometry, work-piece hardness, temperature and rigidity of the machine tool were assumed as constant in the different sets of tests.

The material was selected as mild steel and the size of the work-piece was selected as 80 x 80 x 25 mm. In the pre-machining operations, sequential measurements and inspections involved are hardness testing (diamond indentor type), viscosity measurement (redwood viscometer) and measurement of natural frequency.

Probe available with the vibration analyser VA –10 (Rion make,), is rigidly screwed to the work-piece. The position of the probe on the work-piece is decided such that the maximum oscillations in the horizontal plane produced by cutting action of a tool are sensed effectively with the help of well-positioned sensor. 5 mm drill diameter and M6 tap was used for internal threading for a length of 20 mm and the length of stud for proper contact of work-piece and sensor was kept at 12 mm.

Table 2: Tool X (Hardness 60 Rc, Natural Frequency as 60 Hz)

Exp. no	Viscosity (Cst)	Cutting speed (m/min)	Feed (mm/sec)	No. Of holes	Initial Hz	Final Hz	Initial Ra (Microns)	Final Ra (Microns)
1	33	19.7	0.937	8	180	60	6	6.31
2	33	19.7	1.5	8	125	70	5.89	6.19
3	33	19.7	0.937	15	180	135	5.92	7
4	33	19.7	1.5	15	70	70	4.69	4.89
5	33	27.7	1.31	8	65	175	4.84	5.1
6	33	27.7	2.1	8	65	185	6.1	6.26
7	33	27.7	1.31	15	85	185	6	6.31
8	33	27.7	2.1	15	85	60	4.89	5.32
9	45.6	19.7	0.937	8	135	130	5.89	6.29
10	45.6	19.7	1.5	8	150	135	5.69	6.09
11	45.6	19.7	0.937	15	65	145	5.89	6.85
12	45.6	19.7	1.5	15	55	95	4.61	4.73
13	45.6	27.7	1.31	8	88	66	4.33	4.74
14	45.6	27.7	2.1	8	52	144	4.03	4.94
15	45.6	27.7	1.31	15	140	140	5.89	6.16
16	45.6	27.7	2.1	15	140	140	4.61	5.11

Table 3: Tool Y (Hardness 61 Rc, Natural Frequency as 66 Hz)

Exp. no	Viscosity (Cst)	Cutting speed (m/min)	Feed (mm/sec)	No. Of holes	Initial Hz	Final Hz	Initial Ra (Microns)	Final Ra (Microns)
1	33	19.7	0.937	8	75	45	3.26	4.1
2	33	19.7	1.5	8	70	70	4.26	4.61
3	33	19.7	0.937	15	75	75	4.92	6.1
4	33	19.7	1.5	15	75	75	4.92	6.13
5	33	27.7	1.31	8	65	90	5.93	6.25
6	33	27.7	2.1	8	140	150	5.91	6.13
7	33	27.7	1.31	15	125	125	5.23	4.96
8	33	27.7	2.1	15	130	130	4.74	4.84
9	45.6	19.7	0.937	8	140	140	3.00	3.79
10	45.6	19.7	1.5	8	140	140	4.02	4.29
11	45.6	19.7	0.937	15	55	75	4.89	5.9
12	45.6	19.7	1.5	15	96	110	4.51	4.89
13	45.6	27.7	1.31	8	135	135	5.71	6.00
14	45.6	27.7	2.1	8	135	140	3.88	4.1
15	45.6	27.7	1.31	15	135	135	4.8	5.1
16	45.6	27.7	2.1	15	135	130	4.47	4.57

4. EXPERIMENTAL DATA

Total of 32 drilling experiments with 14mm diameter were carried out on a radial drilling machine and vibration frequency response was recorded for the 1st hole, 5th hole and the 8th hole for 8 hole work-piece and for 15th holes work-piece 1st, 5th, 10th and 15th hole. The vibration analyser setting for running condition was selected as amplitude mode as velocity (mm/sec), averaging mode (linear and number of averages as 10) and span as (500 Hz). The experimental data is as shown in Tables 2 and 3 for tool X and tool Y.

5. ANALYSIS OF EXPERIMENTAL DATA

Factorial regression analysis is used to generalise the relationship of the controllable variables with the response variables. To establish the regression model, the method used was the least square method. The method used is based on the principle that the actual value of response and the predicted value using the model, for the same set of independent variables should be as minimum as possible. The theory uses the application of derivatives so that the solution of the first derivative (with respect to the parameters in the postulated model), which is equated to zero, gives the value greater than zero for the second derivative. The functional relationship between response parameters (R_a and F) of the cutting operation and the integrated independent variables (s, f, n, t) for the postulated model of total experimentation is given by

$$R_a = k\mu^\alpha \ s^\gamma \ f^\delta \ t^\beta \tag{1}$$

$$F = k\mu^\alpha \ s^\gamma \ f^\delta \ t^\beta \tag{2}$$

Where,

R_a - Surface roughness (microns)
F - Frequency response (Hz)
S - Speed (m/min)
f - Feed (mm/sec)
n - Number of holes
μ - Viscosity of lubricants
α γ δ β - Exponents to be determined using regression analysis
K - Co-efficient of regression

The form of Equations (1) and (2) is non linear and hence log transformations of each variables is taken for the purpose of converting them into linear equation.

$$log \ R_a = log \ \mu + \alpha \ log \ \mu + \gamma \ log \ s + \delta \ log \ f + \beta \ log \ t \tag{3}$$

$$log \ F = log \ \mu + \alpha \ log \ \mu + \gamma \ log \ s + \delta \ log \ f + \beta \ log \ t \tag{4}$$

The Equations (3) and (4) may take the form as

$$Y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 \ \text{-------} + \varepsilon \tag{5}$$

Where,

Y is the transformation of true response (R_a and F) on a logarithmic scale x1, x2 and x3 are the transformed independent variables (μ , s, f, t) and is the total error in the experimentation. a1, a2, a3 are the coefficient of logarithmically transformed variables and k is the characteristic coefficient of the generalised equation and it is antilog of a_0

$$\beta = (X^1 .X)^{-1} \ X^1 .Y \tag{6}$$

Where β is the column vector of the the parameter x is the matrix of the transformed independent variables (a_0, a_2, a_3 and a_4) and Y is the column vector of the output variable (R_a and F).

6. STATISTICAL TABLES

The statistical software SPSS is used for the analysis of drilling problem. All the parameters such as multiple R, R Square, Adjusted R Square, Standard error, Regression and Residual were obtained. The summary of statistical output for the final frequency and surface roughness for tool X and tool Y is as shown in Tables 4 to 7.

Table 4: Summary output of final frequency (Hz) for tool X

Regression Statistics					
Multiple R	0.399327				
R Square	0.159597				
Adjusted R Square	0.14546				
Standard Error	0.191105				
Observations	16				
ANOVA					
	df	SS	MS	F	Significance F
Regression	4	0.077029	0.019257	0.523739	0.7206244
Residual	11	0.404165	0.036724		
Total	15	0.481395			
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	2.050462	0.04796	42.78156	1.39E-13	1.94441273	2.15531
X Variable 1	0.031223	0.04796	0.651199	0.52834	-0.742262	0.136672
X Variable 2	0.052709	0.04796	1.100854	0.294738	-0.052739	0.158258
X Variable 3	0.00601	0.04796	0.12578	0.902197	-0.994591	0.111539
X Variable 4	-0.031926	0.04796	-0.6672	0.518784	-0.137422	0.073575

Table 5: Summary output of final frequency (Hz) for tool Y

Regression Statistics					
Multiple R	0.802215				
R Square	0.643588				
Adjusted R Square	0.513902				
Standard Error	0.106979				
Observations	16				
ANOVA					
	df	SS	MS	F	Significance F
Regression	4	0.227754	0.0567897	4.965443	0.0155929 4
Residual	11	0.125729 5	0.0114364		
Total	15	0.352983			
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	2.050462	0.02796	75.78156	2.29E-13	1.96441273	2.15531
X Variable 1	0.071223	0.02796	2.651199	0.022834	0.012742262	0.130072
X Variable 2	0.082709	0.02796	3.100854	0.0074738	0.022739	0.148258
X Variable 3	-0.00401	0.02796	-0.17578	0.862197	-0.064591	0.051539
X variable 4	0.031926	0.02796	1.3672	0.1987	-0.02174	0.09635

Table 6: Summary output of final Ra for tool X

Regression Statistics					
Multiple R	0.790055				
R Square	0.624167				
Adjusted R Square	0.487527				
Standard Error	0.07753				
Observations	16				

ANOVA					
	df	SS	MS	F	Significance F
Regression	4	0.10984	0.02746	4.523739	0.020372
Residual	11	0.066135	0.006014		
Total	15	0.17590 5			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.65698	0.019385	33.78156	1.39E- 13	0.61441273	0.699631
X Variable 1	0.004548	0.019385	0.231199	0.82834	-0.0382262	0.046672
X Variable 2	-0.0696	0.019385	-3.100854	0.004738	-0.112739	-0.028258
X Variable 3	-0.03819	0.019385	-1.978024	0.072197	-0.084591	0.004539
X Variable 4	-0.02328	0.019385	-1.2072	0.258784	-0.067422	0.013575

Table 7: Summary output of final R_a for tool Y

Regression Statistics					
Multiple R	0.589327				
R Square	0.349597				
Adjusted R Square	0.1004546				
Standard Error	0.171105				
Observations	16				

ANOVA					
	df	SS	MS	F	Significance F
Regression	4	0.177029	0.044257	1.423739	0.2906244
Residual	11	0.3404165	0.031724		
Total	15	0.511395			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.550462	0.04496	13.78156	4.39E- 13	0.44441273	0.65531
X Variable 1	0.003223	0.04496	0.071199	0.92834	0.092262	0.106672
X Variable 2	-0.092709	0.04496	-2.100854	0.054738	-0.192739	0.008258
X Variable 3	-0.0401	0.04496	-0.92578	0.352197	-0.134591	0.051539
X Variable 4	0.018926	0.04496	0.4672	0.688784	-0.077422	0.113575

7. MODIFIED REGRESSION EQUATIONS

Equations established by regression analysis are as shown below:

For Drill X: $F = 112.3269\ \mu^{0.0312}\ s^{0.0527}\ t^{0.0067}\ f^{0.0312}$ (7)

For Drill Y: $F = 104.698\ \mu^{0.0713}\ s^{0.0877}\ t^{-0.0047}\ f^{0.0312}$ (8)

For Drill X: $R_a = 4.54\ \mu^{0.0045}\ s^{-1.1196}\ t^{-0.0382}\ f^{-0.0238}$ (9)

For Drill Y: $R_a = 3.76\ \mu^{0.0033}\ s^{-0.0944}\ t^{-0.0422}\ f^{0.0312}$ (10)

The modified regression models used for plotting the graphs are;

For Frequency: $F\gamma X. = 126.42\ s^{0.0527}\ f^{-0.0319}$ (11)

$F\gamma X. = 133.48\ s^{0.0877}\ f^{0.0319}$ (12)

For Surface Roughness $R_a X = 4.26\ s^{-0.0696}\ f^{-0.0232}$ (13)

$R_a Y = 3.48\ s^{-0.0944}\ f^{0.0181}$ (14)

These equations are valid within the region of the experiments and hence can be used to interpolate the response by giving appropriate values of cutting speed and viscosity.

8. VIBRATION SIGNATURES AND GRAPHS

Vibration signatures are recorded with the help of VA 10, FFT analyser in ideal condition as well as in running conditions. The vibration signatures for tool VX (XT0) in ideal condition and (XT1 to XT2) are in running conditions. Similarly for tool VY (YT0) in ideal condition and (YT1 to YT2) are in running conditions are as shown below as V_X and V_Y. The graphs for frequency and surface roughness were plotted, on Y axis cutting speed (m/min) and on X axis as feed (mm/sec). The graphs for frequency were as shown in Figures 1 to 4 and graphs for surface roughness were as shown in Figures 5 to 9.

9. RESULTS AND DISCUSSIONS

The results obtained for predominant vibrations, surface roughness by statistical analysis for tool X and tool Y have been analysed.

a) In case of predominant vibration, the original regression models of Equation (11 and 12) for both the tools are not statistically justified. The errors in the estimated coefficients of the parameters are high and the regression coefficient is low and consequently the patterns of contour plot are not matching adequately for both the tool X and tool Y.

b) In case of tool X predominant vibrations are increasing with increase in cutting speed while the same is decreasing with increase in feed. In case of tool Y predominant vibrations are decreasing with increase in cutting speed while the same is decreasing with increasing feed.

c) While comparing both the tools for vibration it is observed that predominant vibration in case of tool X at natural frequency (Figure XT0) measured in free field conditions, which is getting excited during cutting for all combination of cutting speed and feed (XT0 to XT2). This clearly indicated that more wear of tool X because of resonance and in case of tool Y (Figure YT0), the natural frequency measured in free field condition is not getting excited in any combination of cutting speed and feed. This is justified from (Figure Vy- YT 1 to YT 2).

d) Tool X has lower hardness value of 60 Rc as compared to tool Y, which has a hardness value of 61 Rc. Thus indicating that tool Y is stiffer than tool Y.

e) The regression models (Equations 13 and 14), for surface roughness are not statistically justified. This

may be due to some experimental errors. The regression coefficient is not sufficiently large and the P values (significance values) are high. This may be because of the improper behavior observed by the contour plots. However for same combinations of cutting speed and feed the Ra value is more for tool X as compare to that of tool Y.

CONCLUSIONS

Vibration analysis method can be effectively applied for the quality and performance analysis for drilling tools. Cutting speed. Feed, viscosity, number of holes, natural frequency and surface roughness can be used as a inputs for quality and performance analysis. Based on the statistical analysis and nature of graphs the better quality and performance of the tool is decided. The tool Y is better in design as no natural frequency is getting excited in operating conditions, which is better in quality and performance than tool X, within the range of experimental values and the parameters studied for the above work. ∎

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