Examining the Influence of Cutting Parameters on Tool Life for Tungsten and Molybdenum During CNC Lathe Turning of Mild Carbon Steel When Flank Wear is Present

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***Abstract*—** *This study investigates the effects of cutting parameters on the tool life of two grades of high-speed steel tools, Tungsten (T1) and Molybdenum (T2), during the turning of mild carbon steel on a CNC lathe. Experiments were conducted on mild steel rods (200 mm length, 30 mm diameter) at three feed rates (0.1, 0.2, and 0.3 mm/rev), with a constant depth of cut (0.4 mm) using an 18-spindle rotational speed CNC lathe. Power and linear regression models were employed in MATLAB to determine and validate* R^2 *values. Analysis of variance (ANOVA) was performed to identify the best-fit model for experimental tool lives. Furthermore, chip-tool interface temperatures were modeled and compared with established literature to ensure accuracy and reliability.*

***Keywords*— *ANOVA, Cutting parameters, CNC lathe, High Speed Steel, Tool life*.**

I. INTRODUCTION

Lathe turning operation is probably the most used of all the machining processes. About one third of the machines in production are employed in turning. In a turning operation, the work piece, held in the chuck is rotated and a cutting tool removes the work material strip by strip and then layer by layer as the latter is being turned [11].

Computer-controlled (numerically controlled, NC, CNC) lathes incorporate a computer system to control the movements of machine components by inserting coded instructions in the form of numerical data. A CNC lathe is especially useful in turning operations and precise machining

Some of the cutting conditions that influence tool life and tool wear include the cutting speed, the feed rate and the depth of cut. Much effort has been done to establish the relationship between cutting speed, tool wear and tool life [2]. The cutting speed influences the tool life such that at low cutting speeds, the tool lasts long and the tooling cost is low [3]. But the metal removal rate will be low and hence the cutting cost and the total costs are high. However, at high cutting speeds, the metal removal rate will be high resulting in low cutting cost, shortened tool life and giving high tooling cost [12]. The life of a cutting tool can be terminated by a number of means, although they fall broadly into two main categories;

a) Gradual wearing of certain regions of the face and flank of the cutting tool and

b) Abrupt tool failure.

Considering the more desirable case, the life of a cutting tool is therefore determined by the amount of wear that has occurred on the tool profile, and which reduces the efficiency of cutting to an unacceptable level or causes tool failure. When the tool wears reaches initially an unacceptable level, there is the need to replace the tool with the right geometry in accordance to ISO 5610 standard [7,9].

Excessive increase in the cutting speed will result in the tool wear and increasing the cutting speed increases the rate of production but decreases the tool life the most. [2,6]

Similarly, excessive feed will cause tool wear. Increasing the feed rate will increase the production rate but decrease the tool life the least. [2,6]

Increasing the depth of cut influences the tool life more than increasing the feed does. Therefore, at an intermediate cutting speed, the total cost is at a minimum. The tool life corresponding to the cutting speed is the economic tool life. Values for the machining variables traditionally used by industry may gradually be replaced with values based on economic considerations. Only continuous research in this area and the application of the results, whether it is directly or by handbook revisions, will enable Manufacturing organizations to operate economically under the ever- increasing production requirements of today [12].

II. TOOL LIFE MODELS USED FOR DATA EVALUATION

The relationship between the tool life and the machining independent variables, cutting speed, and feed rate can be represented by the following equations:

$$\mathrm{T} = \mathrm{K}\mathrm{V}^{\mathrm{a}}\epsilon \tag{1}$$

$$\mathrm{T} = \mathrm{K}V^{a}f^{b} \in \tag{2}$$

Where T is the response variable, tool life in minutes, V and f are the cutting speed in meters per minute (m/min) and feed rate in millimeters per revolution (mm/rev). K, a, b are constants and ∈ is the random error having normal distribution with zero mean. To facilitate the determination of constants and parameters, the mathematical models will be linearized by performing logarithmic transformation [13]

This research considers the flank wear of the High-Speed Steel tool as Linear, Quadratic, Polynomial, power, logarithmic, and exponential regression models using MATLAB to validate and find their R^2 values. Analysis of variance was developed for each tool to predict the model that will give the closest fit compared with the experimental tool lives.

The Chip-tool interface temperatures were also modeled and compared with the measurements from established literature.

2.1 Linear Model:

In fitting a linear regression model, there are just two variables; (the independent and the dependent variables).

Starting from

$$y = mx + k \tag{3}$$

Where,

x = cutting time (min)

y = Flank wear (mm)

k and m are regression coefficients to be determined.

Applying regression techniques to evaluate “m” and “k”, the error sum of squares (SSE) can be expressed as:

$$SSE = \sum_{i=1}^{n}(y_0 - mx - k)^2 \tag{4}$$

Differentiating equation (4) with respect to m and k respectively and equating it to zero yields the following normal equations

$$\sum_{i=1}^{n} y_i \ + m\sum_{i=1}^{n} x_i + nk \tag{5}$$

$$\sum_{i=1}^{n} x_i y_i = m\sum_{i=1}^{n} x_i^2 + k\sum_{i=1}^{n} x \tag{6}$$

Solving these normal equations simultaneously gives the values of m and k respectively.

2.2 Power Model:

Power model of the general form

$$y = ax^k \tag{7}$$

is assumed.

Where,

y = Flank wear, x = cutting time.

a and k are the regression coefficients to be determined [14].

Transforming equation (7) by taking logarithms of both sides of the equation gives;

$$Log\mathrm{y} = Log\mathrm{a} + kLog\mathrm{x} \quad (8)$$

Equation (8) can then be compared with the straight-line general equation, applying the same procedure to determine the coefficients.

2.3 Exponential Model:

An exponential equation of the general form

$$y = ae^{bx} \quad (9)$$

is assumed.

Where,

y = Flank wear

a and b are regression coefficients to be determined. Smith [14].

Transforming equation (9) by taking the natural logarithms of both side of the equation gives

$$Iny = Ina + bx \quad (10)$$

Equation (10) can be compared with straight line general equation and the same procedure is applied to determine the coefficients.

2.4 Quadratic Model:

A general form of the Quadratic equation

$$y = k + bx + ax^2 \quad (11)$$

is assumed.

Applying the regression techniques to evaluate a, b and k in equation (11), yields

$$SSE = \sum_{i=1}^{n}(y_0 - k - bx - ax^2)^2 \quad (12)$$

$$SSE = \sum_{i=1}^{n}(y_0 - k - kb - ax^2)^2 \quad (13)$$

Differentiating equation (12) with respect to a, b and c in turn and equating it to zero yields the following normal equations.

$$\sum_{i=1}^{n} y_i = nk + b \sum_{i=1}^{n} x_i + a\sum_{i=1}^{n} x_i^2 \quad (14)$$

$$\sum_{i=1}^{n} x_i y_i = k\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} x_i^2 + a\sum_{i=1}^{n} x_i^3 \quad (15)$$

$$\sum_{i=1}^{n} x_i^2 y_i = k\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i^3 + a\sum_{i=1}^{n} x_i^4 \quad (16)$$

The coefficients of the regression model can then be determined by solving these normal equations simultaneously [14].

III. EXPERIMENTAL SETUP

The experiment was set up with a tailstock and a running center to hold the workpiece at one end, and a 4-jaw chuck to secure the workpiece at the other end. The tool was positioned on the tool post for the orthogonal cutting. This study aimed to determine the influence of cutting conditions on the tool life of High-Speed Steel (HSS) cutting tools during the turning of mild carbon steel at various cutting speeds and feed rates.

A standard chromel-alumel thermocouple, inserted near the rake face of the tool, was used to measure the interface temperatures. An experimental design based on the 2^2 factorial method was applied to evaluate the cutting speed and feed rate. The tests were conducted under a constant depth of cut of 0.4 mm and dry cutting conditions. According to Erik et al. [6], the depth of cut has the least effect on tool life, so the heaviest possible depth of cut should always be used. Therefore, a pre-cut of about 0.1 mm depth of cut was performed on each workpiece using a different HSS tool to remove the rust layer from the outer surface of the mild steel and minimize any effect of inhomogeneity on the experimental results.

The mild steel rods were fixed to a four-jaw chuck one after the other, center drilled, and set up with a running center to avoid wobbling of the workpiece and achieve accurate results. The speeds and feed rates were selected before starting the turning operation. A stopwatch was used to record the initial time in minutes when the machine began cutting, and it was stopped when the tool could no longer cut and made a squeaking noise. The flank wear was evaluated according to the flank wear model given by Peres et al [5].

A design comprising seven experiments was chosen. Four of these experiments form a 22 factorial design with an additional center point repeated three times, allowing for an assessment of process stability, inherent variability, and curvature checking. The general guideline suggests adding 3 to 5 center point runs to your design [10]. This design incorporates three levels for each independent variable.

IV. RESULTS AND DISCUSSION

The Tool life models have been developed using Matlab. The models have been validated by finding their R^2 values. The Matlab code used to determine the analysis of variance is presented in Appendix C. These models and their R^2 values are presented in Appendix E1 and E2 which also show the analysis of variance for the tool life for both the power and the linear models.

Figures 1, 2 and 3 show the graphs of tool life against the Cutting Speed at feed rates of 0.1, 0.2, and 0.3mm/rev for the High Speed Steel grade T1.

The tool life models developed and the R^2 values for high speed steel grade T2 are tabulated in Appendix E2, which also show the analysis of variance for tool life models.

The graph of tool life against cutting speed was plotted at feed rates of 0.1, 0.2 and 0.3 mm/rev. Figures 4, 5 and 6 show the graphs of tool life against cutting speed at various feed rates.

TABLE 1
CHEMICAL COMPOSITION OF MILD CARBON STEEL ROD USED (RST 34-2)

C	Mn	Si	P	S	Cu	Fe
0.08-0.15	0.20-0.50	0.03-0.30	0.05 Maximum	0.05 Maximum	Traces	Balance

(Source: Scientific Equipment Development Institute (SEDI), Minna).

4.1 Results of Tool Life Models for High Speed Steel Tool, T1:

The Tool life models have been developed using MATLAB. The models have been validated by finding their R^2 values. The MATLAB codes were used to determine the analysis of variance. These models and their R^2 values are presented in Table 2 for the high-speed steel grade, T1. Table 3 and Table 4 show the analysis of variance for the tool life for both the power and the linear models.

TABLE 2
TOOL LIFE MODELS AND R^2

S/N	Model	Equation	R^2
1	Power	$T = 723.935\ V^{-0.8544}\ f^{-0.02}$	0.96
2	Linear	$T = 95.9102-1.2501\ V-18.625f$	0.6

TABLE 3
ANALYSIS OF VARIANCE OF POWER MODEL FOR TOOL LIFE

Source	SS	DF	MS	F
A(Speed)	0.358	1	0.358	0.7192
B(feed rate)	7.21E-04	1	7.21E-04	1.45E-03
AB(Interaction)	1.58E-04	1	1.58E-04	3.17E-04
Curvature	0.055	1	0.055	0.1105
Error	1.9911	4	0.4978	
Total	2.405			

TABLE 4
ANALYSIS OF VARIANCE OF LINEAR MODEL FOR TOOL LIFE

Source	SS	DF	MS	F
A(Speed)	4571.78	1	4571.78	18.826
B(feed rate)	20.026	1	20.026	0.0824
AB(Interaction)	13.876	1	13.876	0.0571
Curvature	43.588	1	43.588	0.1795
Error	971.37	4	242.84	
Total	5620.6			

Figures 1, 2 and 3 show the graphs of tool life against the Cutting Speed at feed rates of 0.1, 0.2, and 0.3mm/rev for the High Speed Steel grade T1.

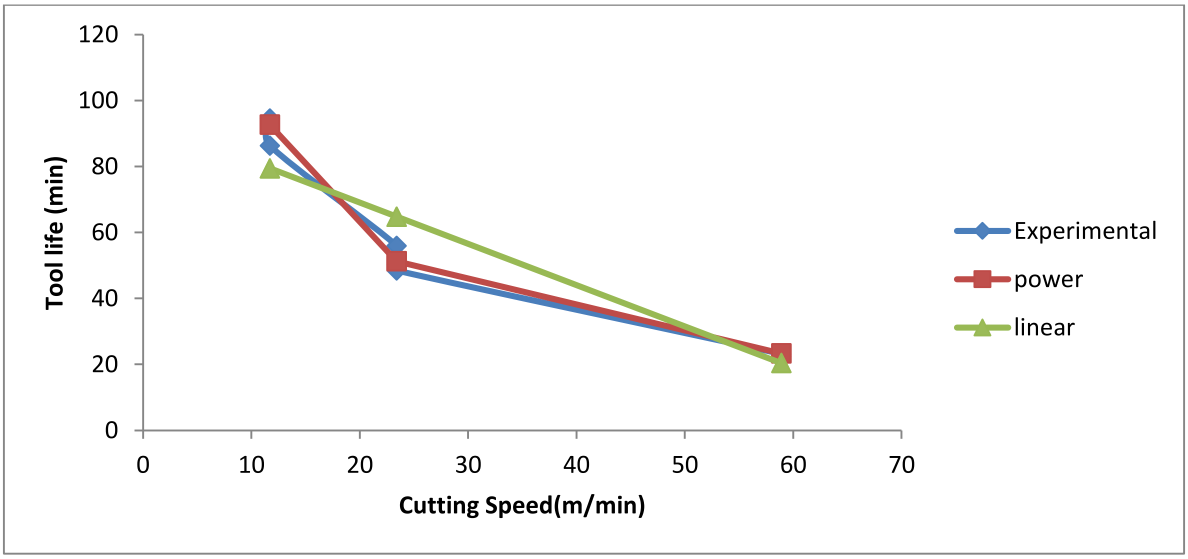

FIGURE 1: Graph of Tool life against Cutting Speed at feed rate of 0.1 mm/rev

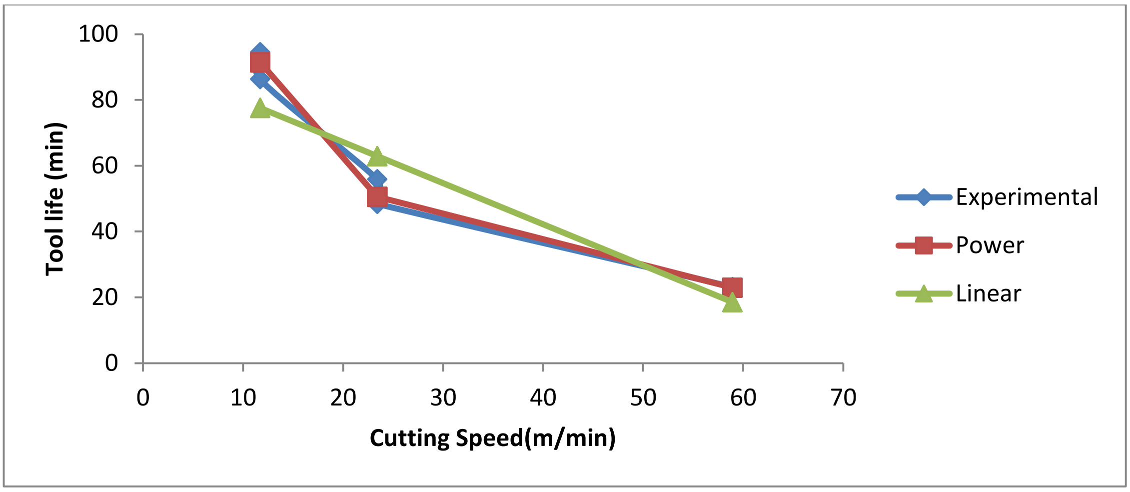

FIGURE 2: Graph of Tool life against Cutting Speed at feed rate of 0.2 mm /rev

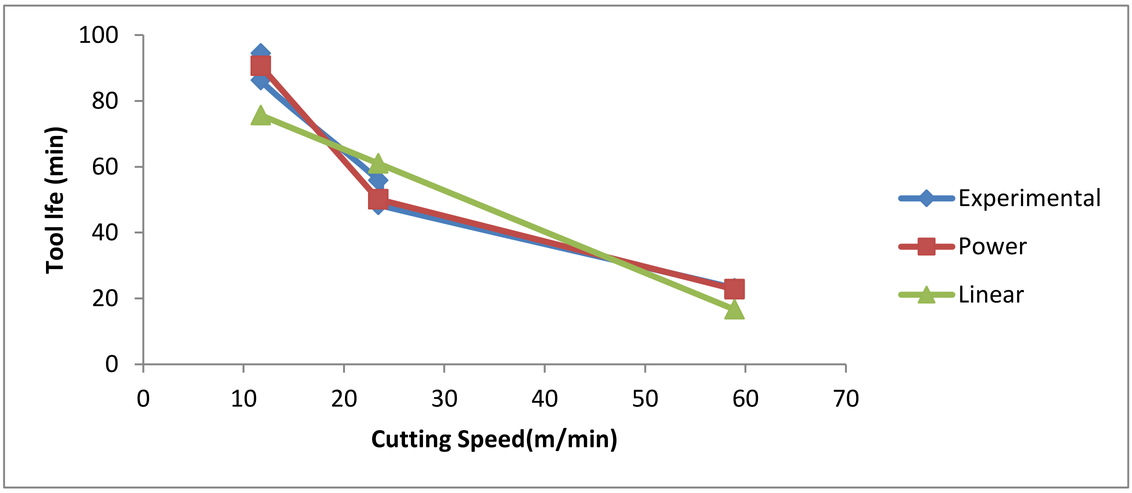

FIGURE 3: Graph of Tool life against Cutting Speed at feed rate of 0.3 mm/rev

4.2 Results of Tool Life Models for High Speed Steel Tool, T2

The tool life models developed and the R^2 values for high speed steel grade T2 are tabulated in table 6. Tables 6 and 7 show the analyses of variance for tool life models.

TABLE 6
TOOL LIFE MODELS AND R^2

S/N	Model	Equation	R^2
1	Power	$T = 1408.96\ V^{-1.0496}\ f^{-0.0049}$	0.95
2	Linear	T = 108.2406-1.5429V-16.75f	0.7

TABLE 7
ANALYSIS OF VARIANCE OF POWER MODEL FOR TOOL LIFE

Source	SS	DF	MS	F
A(Speed)	0.53377	1	0.53377	1.1526
B(feed rate)	2.33E-04	1	2.33E-04	5.04E-04
AB(Interaction)	1.83E-04	1	1.83E-04	3.94E-04
Curvature	0.01806	1	0.01806	0.03899
Error	1.8527	4	0.4631	
Total	2.405	8		

TABLE 8
ANALYSIS OF VARIANCE OF LINEAR MODEL FOR TOOL LIFE

Source	SS	DF	MS	F
A(Speed)	6844.25	1	6844.25	-21.354
B(feed rate)	11.6964	1	11.6964	-0.0365
AB(Interaction)	11.225	1	11.225	-0.035
Curvature	35.4617	1	35.4617	-0.1106
Error	-1282.036	4	-320.509	
Total	5620.6			

The graph of tool life against cutting speed was plotted at feed rates of 0.1, 0.2 and 0.3 mm/rev. Figures 4, 5 and 6 show the graphs of tool life against cutting speed at various feed rates.

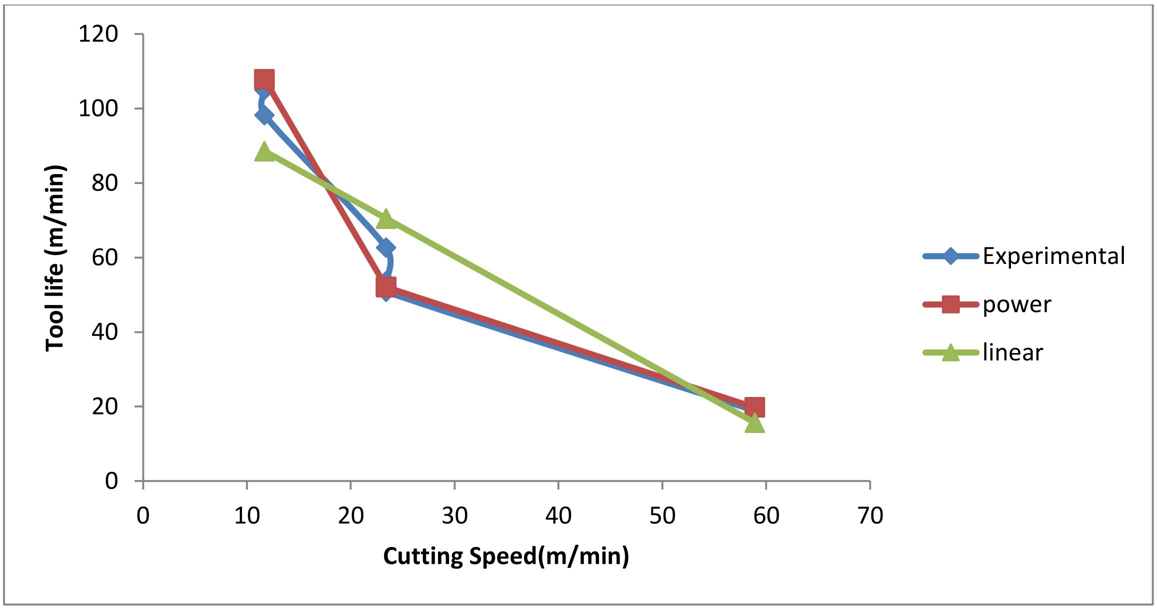

FIGURE 4: Graph of Tool life against Cutting Speed at feed rate of 0.1 mm/rev

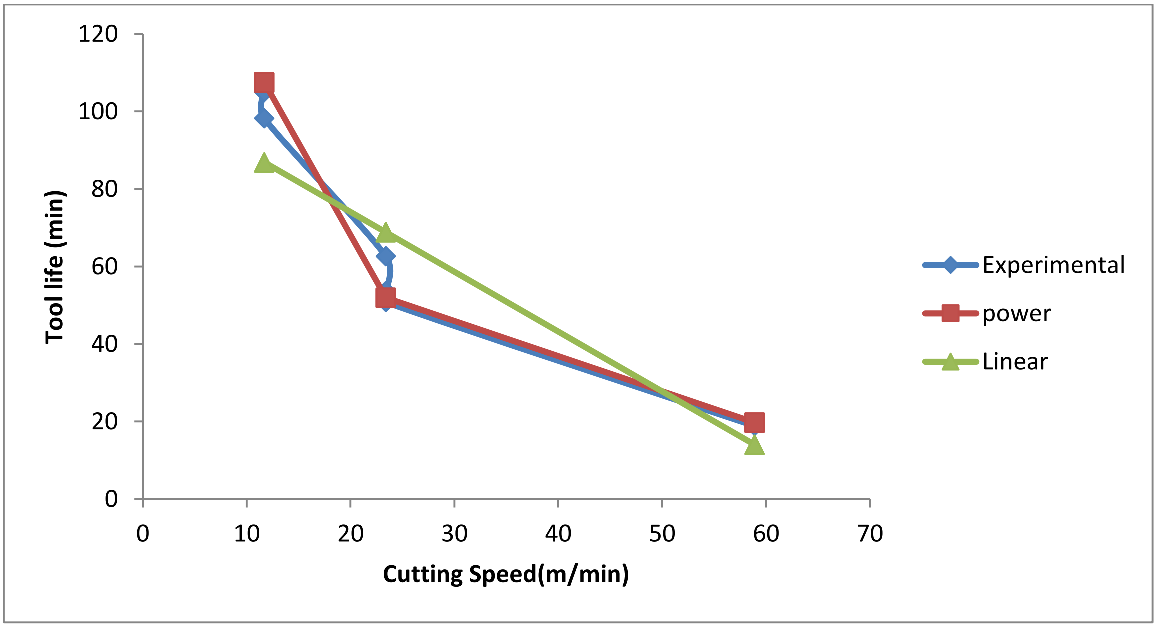

FIGURE 5: Graph of Tool life against Cutting Speed at feed rate of 0.2 mm/rev

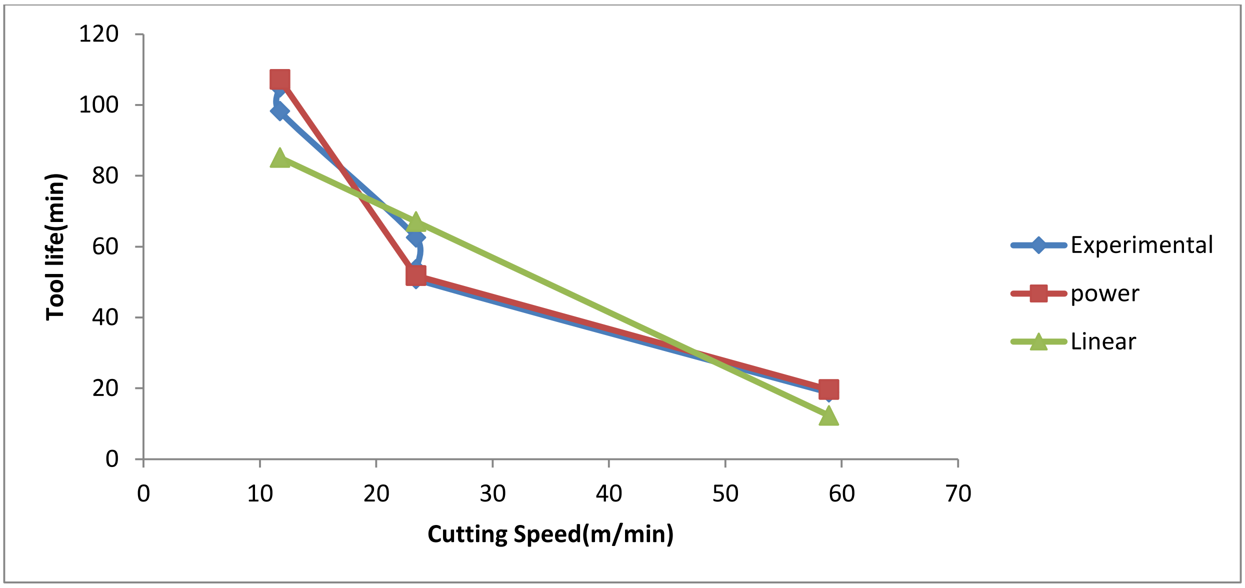

FIGURE 6: Graph of Tool life against Cutting Speed at feed rate of 0.3 mm/rev

The tool life model developed based on the experiments is given in equation (17)

$$T = 723.935\, V^{-0.8854} f^{-0.02} \quad (17)$$

V. CONCLUSION

Two Tungsten grades of High-speed steel tools were used to machine mild steel rods at various combinations of cutting speeds and feed rates to determine their influence on tool life. The conclusions drawn are as follows

1) The effect of feed rate and cutting speed on tool life was studied successfully. The power and linear regression models were developed for each tool. The power regression model gave the closest fit compared with the experimental tool lives. The R^2 values for the T1 grade are 0.96 for power model and 0.60 for the linear model. For T2, the R^2 values of 0.95 and 0.70 were found for power and linear model respectively. It is therefore adequate to predict the tool life with power regression model.

2) The power model gave the highest R^2 values throughout the prediction of flank wear. It is, therefore, the best to use for prediction of tool life. All the other regression models are also adequate for prediction of flank wear.

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