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Prediction of Tool-Life Model for Heavy Machining Using Central Composite Design

Vipin[1], Priya[2]

[1](Prod. & Ind. Engineering, Delhi Technological University, Delhi, India)
[2](Mahavir Sawami Institute of Technology, Sonipat, Haryana, India)
[1]vipin2867@yahoo.co.in

Abstarct : *The paper presents a study for tool-life models for turning cast steel material with uncoated cemented carbide tool. In this heavy machining operation under dry conditions with varying depth of cut between 5-10 mm is used. The tool-life models have been developed from the data obtained experimentally in terms of cutting speed, feed rate and depth of cut using factorial design method and regression analysis.*

Keywords: *Tool-life, cutting speed, feed, depth of cut, metal removal rate.*

I. INTRODUCTION

For the design of cutting tools; ability to predict the tool life during machining is necessary. This involves determination of tool changing strategies and optimum cutting conditions. The extensive research in this area has contributed greatly for understanding the problem. There is no machining theory provide adequate relationships between work and tool material properties, tool-life and cutting conditions and, tool geometrical parameters. The major difficulties are the lack of suitable data and complexity of the machining process. Tool life depends on a number of variables i.e. machine tool, tool material and geometry, microstructure of work material being cut, the desired cubic-inch removal rate, cutting conditions and whether or not cutting fluids are used, etc. No machining theory is available to predict the tool life for a practical machining situation.

Researchers Hassan and Suliman [1990], Chua *et al* [1993], Lin and Chen [1995], Choudhury and El-Baradie [1998], Santos *et al* [1999], Ozler *et al* [2001], Lima *et al* [2005], Vipin et al [2009] worked on predicting the tool-life. However the models developed by these Researchers are mostly empirical relations between cutting speeds, feeds and varying depth of cuts up to 5mm. These models are silent with regards to heavy machining process for depth of cut above 5mm. Ranganath M. S. et al [2014], Ranganath M. S. et al [2014] worked on Response Surface Methodology.

The present work therefore emphasis to develop mathematical models to predict tool life equation for medium and heavy machining operation for depth of cut between 5 to 10 mm. The depth of cut, feed rate and cutting speed were obtained from double column heavy vertical boring and turning machine for turning operations on work of 3.6m diameter, EN6 cast steel material. The data so obtained was used to develop Tool life equation with the help of Central composite Design.

First- and second-order models are developed with 95% confidence level by using response surface methodology and 2^3 factorial design of experiment. 3D plots of tool-life, and dual-response contours of metal removal rate and tool life for different cutting conditions are developed by the model equations.

II. TOOL LIFE MODEL

The proposed relationship between the machining response (tool life) and machining independent variables can be represented by the following:

$$T = C(V^{\alpha} f^{\beta} d^{\gamma})\zeta \qquad (1)$$

where T is the tool life in minutes, V is cutting speeds (m/min),
f is feed rates (mm/rev), d is depth of cut (mm)
C, α, β, γ are constants, ζ is a random error.

Equation (1) can be rewritten in the following logarithmic form:

$$\log T = \log C + \alpha \log V + \beta \log f + \gamma \log d + \log \zeta \qquad (2)$$

The linear model of Eq. (2) is:

$$y = a_0 x_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + \psi \qquad (3)$$

where y is the measured tool life for a logarithmic scale, x_0 = 1 (dummy variable),
and $x_1 = \log V$, $x_2 = \log f$, $x_3 = \log d$,

$\psi = \log \zeta$, where ψ is random error with zero mean and constant variance,
$a_0 = \log C$, and a_1, a_2, and a_3 are the model parameters.

The estimated response can be written as:

$$y_1 = y - \psi = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \qquad (4)$$

where y_1 is the estimated response,

and b_0, b_1, b_2, and b_3 are estimates of a_0, a_1, a_2, and a_3 respectively.

The Quadratic model for machining response (tool life) is expressed as:

$$y_1 = y - \psi = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \quad \text{------(5)}$$

Equation (5) is useful when the two-way interactions between V, f, and d are significant for second-order effects.
The parameters of Equations (4) and (5) have been estimated by the regression analysis as per the scheme given below in Fig. 1.

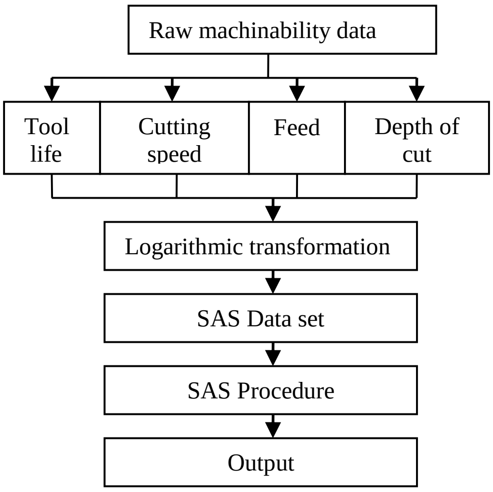

Fig. 1. Program for processing data vector in regression analysis [Vipin and Kumar, 2009]

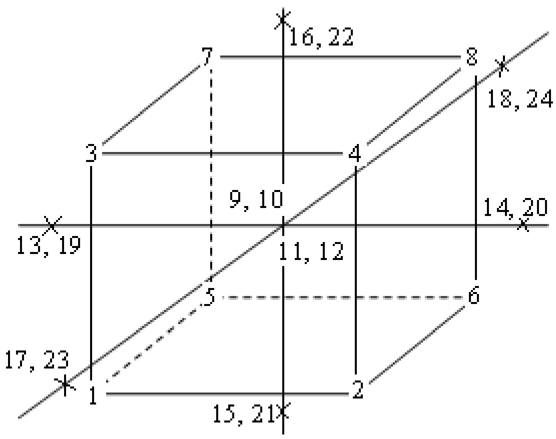

Fig.2. Representation of 2^3 Central design

III. EXPERIMENTAL SETUP

The first-order model was developed by an experimental design consisting of 12 experiments. Twelve experiments constitute Eight experiments (2^3 factorial designs) and Four experiments (an added centre point repeated four times) as shown in Fig.2. This was done to predict the 'b' parameters as used in the Equation (4). The blocks provide the confidence interval of the parameters and help in the analysis of variance. A second-order model is developed by adding six augment points to the factorial design. Depending on the capacity of the machine, an augment length of ±1 was chosen. The augment points consist of three levels for each of the independent variables denoted by -1, 0, 1. These six experiments were repeated twice to develop the second-order model. The resulting 12 or 24 experiments form the central composite design Fig. 2 shows 2^3 designs. (Vipin *et. al.* [2009])
Double column heavy vertical boring and turning machine was used to perform the experiment with a 125 hp motor shown in Fig. 3. The machine has the capability to accommodate up to 4m diameter and height up to 6m length. The present investigation was carried out on the work piece of 3.6m diameter and height of 5m. The cutting tool used was a P-40 uncoated cemented carbide insert (SNMA 25 07 24) with tool holder (PSBN 50, 50 T 25). The work piece material was cast steel (EN 6).
The experimentation was performed using cutting tool having fresh cutting edge each time under dry cutting. As the cutting edge of the insert had worn out, machine was stopped. The time of wear of cutting tool was recorded accordingly. The time between two successive tool failures and of each cut was recorded for further investigation.

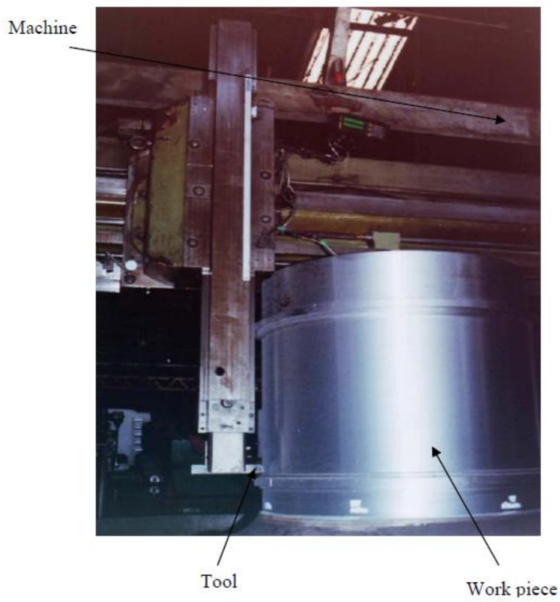

Fig.3. Double Column heavy vertical Boring and Turning Machine

Table 1. Levels of independent variables

Level	Low	Medium	High
Coding	-1	0	1
Cutting speed (m/min) V	75	90	105
Feed (mm/rev) f	0.6	0.8	1.0
Depth of cut (mm) d	6	8	10

III. RESULTS & ANALYSIS

The levels of independent variables and coding are presented in Table 1. The experimental cutting conditions together with measured tool life values are shown in Table 2.

Table 2. Experimental conditions and results

Trial No.	Coding			Tool life (min) T
	x_1	x_2	x_3	
1	-1	-1	-1	42
2	1	-1	-1	21
3	-1	1	-1	33
4	1	1	-1	19
5	-1	-1	1	32
6	1	-1	1	16
7	-1	1	1	25
8	1	1	1	14
9	0	0	0	21
10	0	0	0	20
11	0	0	0	19
12	0	0	0	22
13	-1	0	0	32
14	1	0	0	17
15	0	-1	0	23
16	0	1	0	19
17	0	0	-1	26
18	0	0	1	20
19	-1	0	0	31
20	1	0	0	18
21	0	-1	0	22
22	0	1	0	21
23	0	0	-1	27
24	0	0	1	19

First-order model

The predicted tool life model for the first 12 block obtained in coded form is:

$$y' = 5.65\,x_0 - 1.96\,x_1 - 0.36\,x_2 - 0.56\,x_3 \qquad (6)$$

Table 3. Analysis of variance for 12 tests

Source	DF	SS	MS	F	P
Regression	3	0.194209	0.064736	42.25	0.000
Residual Error	8	0.012257	0.001532		
Lack of Fit	5	0.010257	0.002051	3.08	0.192
Pure Error	3	0.002000	0.000667		
Total	11	0.206467			

Table 3 shows the analysis of variance with the ratio of lack of fit to pure error i.e. F-statistics is 3.08, whilst the P-statistics is 0.192. The model is adequate for determination of tool life prediction. Equation (6) has been transformed in terms of V, f and d for tool life as

$$T = 446683.592\, V^{-1.96} f^{-0.36} d^{-0.56} \qquad (7)$$

Metal removal rate Q (cm^3/min) is given as:

$$Q = V \,.\, f \,.\, d \qquad (8)$$

Tool life decreases with the increase of cutting speed, feed and depth of cut. Cutting speed is the dominant factor, followed by depth of cut and feed because of the respective values of exponents.

Equation 7 is utilized to develop 3D tool-life plots shown in Fig. 4(a)-(c) for different cutting speed, feed and depths of cuts. These 3D plots help to predict the tool life at any zone of the experimental domain.

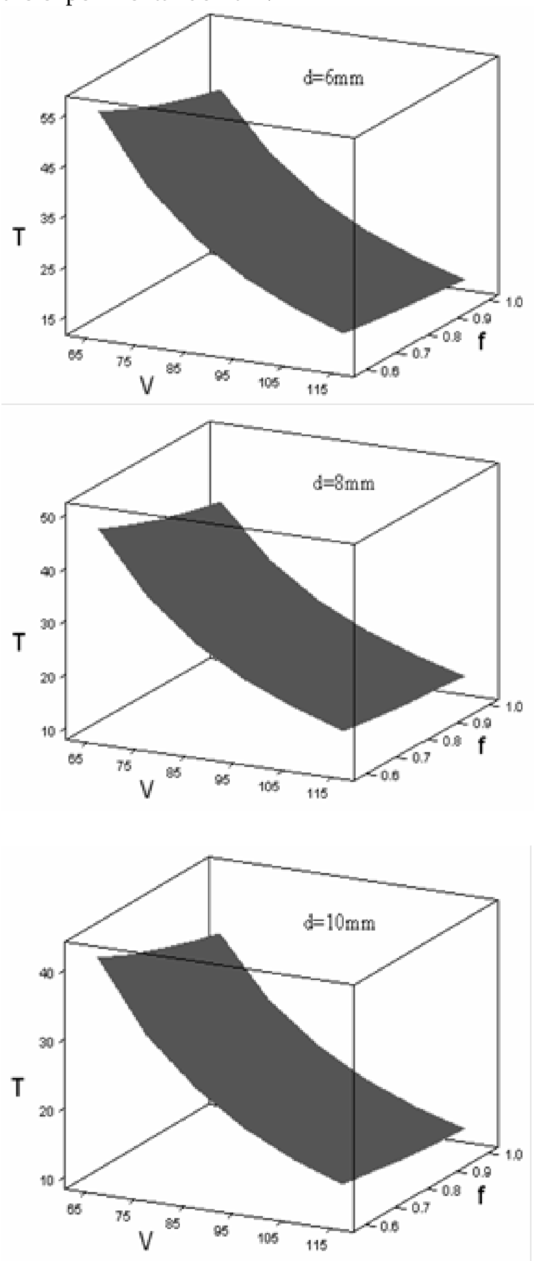

Fig. 4. 3D plots of first-order tool life model at different cutting speed and feed

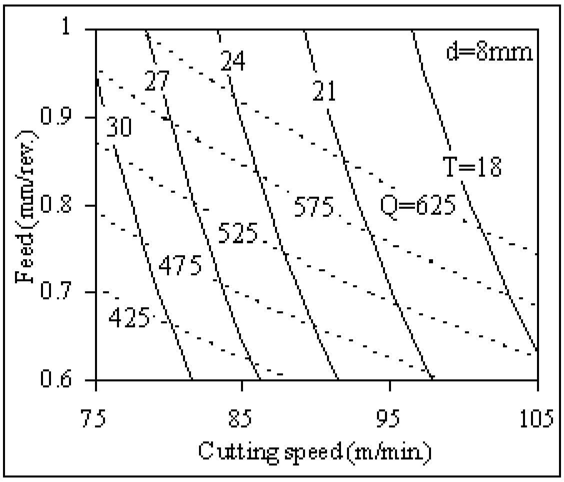

Fig. 5. First-order cutting speed- feed plane for 8.0mm depth of cut

For develop tool-life and metal removal rate contours respectively in the cutting speed–feed plane for depth of cut 8.0mm equation 7 and 8 used as shown in Fig. 5. These contours are used to predict beforehand the tool life and metal removal rate at any zone of the experimental domain. One can also use these contours for comparing various Tool-lives to predict the cutting parameters for predetermined metal removal rate.

Second-order model

First-order model was found to be adequate; the second-order model was postulated to extend the variables range in obtaining the relationship between the tool life and the machining independent variables. The model was based on the central composite design with added augment points to the nucleus of the design. The distance of the augment points was 1 unit.

The model equation is given by:

$$y' = 0.19 + 9.28x_1 - 3.54x_2 - 14.7x_3 - 2.79x_1^2 + 0.018x_2^2 + 7.52x_3^2 + 1.73x_1x_2 + 0.382x_1x_3 - 0.182x_2x_3 \quad (9)$$

Tables 4 indicates the analysis of variance for the ratio of lack of fit to pure error i.e. F-statistics is 1.28, whilst the P-statistics is 0.353. The second-order tool life was explained by the model with factors V, f and d.

Table 4. Analysis of variance for second-order model

Source	DF	SS	MS	F	P
Regression	9	0.290672	0.032297	65.31	0.000
Residual Error	14	0.006923	0.000495		
Lack of Fit	5	0.002873	0.000575	1.28	0.353
Pure Error	9	0.004050	0.000450		
Total	23	0.297596			

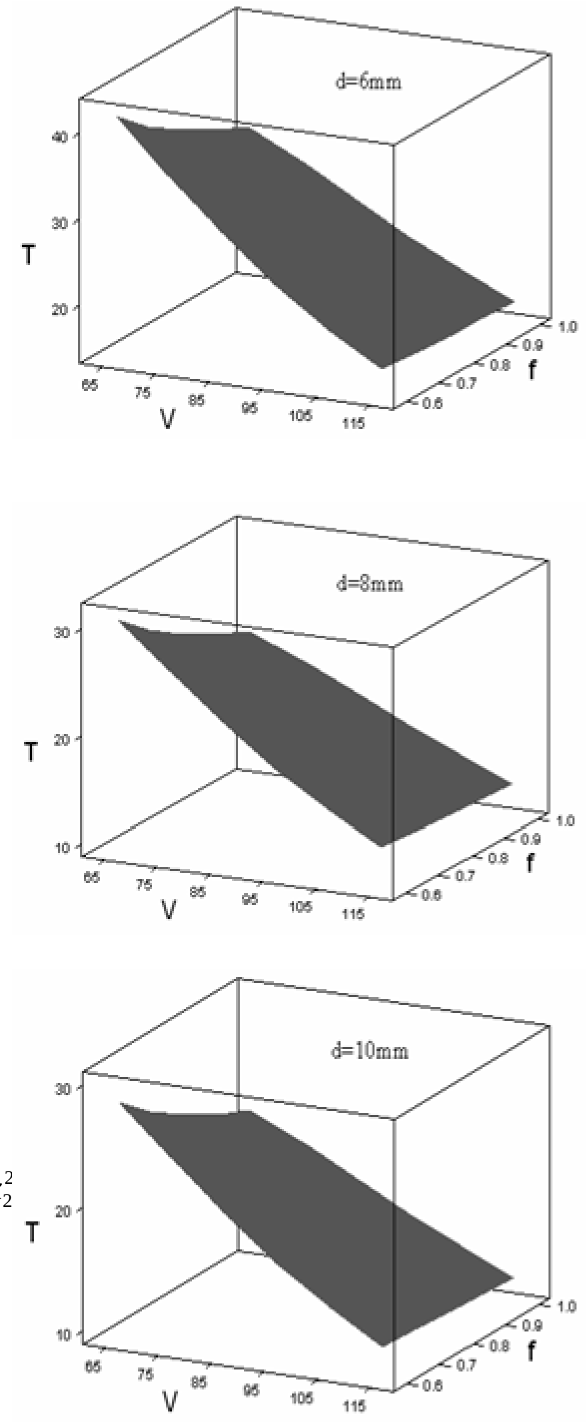

Fig. 6. 3D plots of second-order tool life model at different cutting speed and feed

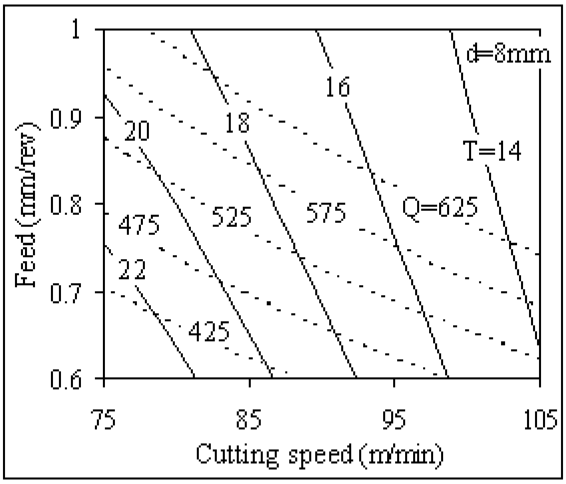

Fig. 7. Second-order cutting speed- feed plane for 8.0mm depth of cut

The model Eq. (9) is plotted in the speed–feed plane for three selected levels of depth of cut in Fig. 6(a)–(c). The contours do not show any sign of non-linearity and thereby confirm that the first-order model is adequate. The contours do not show any sign of non-linearity and thereby confirm that the first-order model is adequate for the present context. Figure 7 is a plot of the dual response of metal removal rate and tool life.

V. CONCLUSIONS

a) Regression analysis has been successfully used to develop the predict tool life.
b) The tool-life equation shows that the cutting speed is the main influencing factor on the tool wear, followed by depth of cut and feed in the operation model. Increasing any of these three cutting variables reduces the tool life.
c) The tool-life contours/results are useful in determining the optimum cutting conditions for a given tool life.
d) Dual-response contours provide useful information about the maximum attainable tool life for a given metal removal rate as a function of all three independent cutting variables.

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