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TOOL LIFE PREDICTION IN THE TURNING OF MEDIUM CARBON STEEL USING HIGH-PRESSURE COOLANT BY FACTORIAL DESIGN OF EXPERIMENTS

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ABSTRACT

This paper discusses the development of tool life prediction model for turning medium carbon steel utilizing response surface methodology. A factorial design technique has been used to study the effects of the main cutting parameters such as cutting speed and depth of cut on tool life. The tests have been carried out using uncoated carbide inserts under high-pressure coolant condition. A first-order prediction model within the speed range of 133-266 m/min has been presented. The results reveal that response surface methodology combined with factorial design of experiments is a better alternative to the traditional one-variable-at-a-time approach for studying the effects of cutting variables on responses such as surface roughness and tool life. This significantly reduces the total number of experiment

Keywords: Tool life, Medium carbon steel, High-pressure coolant, Response surface method

1. INTRODUCTION

In the modern era of intense competition, reduction of machining cost is the key to sustain. For this, the performance of cutting tool plays a vital role. The life of the cutting tool has a large influence on the economics of the machining operations. However, cutting tools have a limited life due to inevitable wear and consequent failure and avenues must be found to determine tool life and the critical parameter of the cutting process. Thus, knowledge of tool wear mechanisms and capability of predicting tool life are important and necessary in metal cutting.

Reliable modeling of tool life is always a concern for machining processes. In general, tool wear model in literature can be classified in to two basic approaches. A relatively new wear rate model approach like Takeyama and Murata wear model (considering abrasive wear and diffusive wear) and Usui wear model (considering adhesive wear) [1] are developed as a function of output state variables like cutting temperature, normal stress, cutting velocity, sliding speed. These models deals with machining outputs with a view to predict amount of tool wear. As these models cannot predict the tool life before the rate of wear before the machining commences, they are of little practical applications. The other approach-empirical tool life models are developed as a function of input cutting parameters. The earliest model in this approach is Taylor's equation; a simple relationship was established for the cutting speed and tool life. Later, it was extended to numerous forms when considering other parameters in cutting. As tool life is directly related to the wear behavior of the cutting tool to predict life, it is necessary to identify the actual wear progress under practical cutting conditions [1]. In metal cutting, the tool wear at the cutting edge is classified as flank wear, crater wear, nose wear, and chipping [2]. Crater wear is a temperature dependent process and dissolution and diffusion mechanisms have been postulated for it by Naerheim and Trent [3]. Flank wear, on the other hand, is commonly due to friction between the tool and the work piece. It is a major form of tool wear in metal cutting. Flank wear may be due to adhesive wear or abrasive wear caused by the hard second phases in the work material [4]. Tool flank wear is found to have detrimental effects on surface finish, residual stresses and microstructural changes in the form of a rehardened surface layer (often referred to as white layer) [5]. Therefore, tool flank wear land width is often used to characterize the tool life.

Recognizing that rise in temperature affects detrimentally to both surface roughness and tool life in terms of increased tool wear rate, different methods are adopted to remove the heat generated during machining. In wet machining, high cutting zone temperature is reduced by employing flood cooling by soluble oil. In high speed-feed machining, conventionally applied cutting fluids fail to penetrate the chip-tool interface and thus cannot remove heat effectively [6]. Moreover, wet machining, now a day, is discouraged due to environmental concerns regarding the disposal of the coolant. Cryogenic cooling by liquid nitrogen jet is reported to play a favorable role in reducing cutting temperature, providing better surface finish and improving tool life compared to dry machining [7, 8]. However, the cost and availability of liquid nitrogen limit the practice of cryogenic machining in experimental and sophisticated machining applications. The use of minimum quantity lubrication (MQL) is more efficient in reaching the chip-tool interface than the flood cooling. But, in addition to environmental concerns about use and disposal of coolant, the mist of coolant generated poses a serious health hazards. Application of high pressure cooling (HPC) in machining is relatively a new approach compared to dry, wet, cryogenic and even MQL. In closed environment like modern NC machines, use of high pressure cooling jet is a promising option. The high-pressured liquid gets more access to the machining zone than other machining and thereby able to remove more heat to provide better machining performance.

Machining with high-pressure coolant environment is perceived to yield favorable machining performance. Relations between technical input variants like speed, feed and depth of cut and resultant performance in terms of tool wear, tool life and surface roughness in turning of commercially available steels using widely available uncoated carbide inserts could contribute in industrial applications along with theoretical understanding. This research aims to develop empirical models for tool life for a predetermined amount of wear and surface roughness for turning steel with uncoated carbide insert by industrially recommended process parameters under high-pressure coolant condition. An experimental study would be conducted to establish and validate the proposed model. The model would be able to predict the tool life and surface roughness from the input technological parameters i.e. speed, feed and depth of cut.

Earlier investigators have studied the effect of cutting variables such as speed, feed and depth of cut on surface roughness by taking one variable at a time, which requires the carrying out of many tests in order to be able to draw a conclusion. Optimum cutting conditions are important since they determine to a great extent, the tool life of the machined parts. However, the response surface methodology (RSM) takes into account the simultaneous variation of the cutting variables and predicts the machining response (the tool life). RSM is a statistical method used for analysis is a combination of the design of experiments and regression analysis and statistical inferences. Wu [9] first pioneered the use of response surface methodology in tool life testing. The number of experiments required to develop a surface roughness equation can be reduced markedly as compared to the traditional one-variable-at-a-time approach. Due to the success of RSM, a number of researchers have utilized it to solve the surface roughness prediction problem. Choudhury and EI-Baradie [10] used this method to predict surface roughness in turning high-strength steel. Feng and Wang [11] applied this method to finish turning. The present study takes into account the simultaneous variation of the cutting variables (cutting speed and feed) and predicts the machining response (the tool life). Based on response surface methodology and 2^2 factorial (2 factors, 2 levels) designs, a first-order model has been developed in this paper. Only four tests were required to develop the first-order model and additional three test were performed to estimate the amount of error of the model.

2. TOOL LIFE MODEL

2.1 Experimental design and conditions

The proposed relationship between the tool life and the machining independent variables speed and feed can be represented by the following equation:

$$T = CV^m S_0^{\,n} \in \text{...}(1)$$

where T is the response variable tool life in minutes. V and S_0 are the cutting speed (m/min) and feed (mm/rev). C, m, n are constants and $\in$ is random error having normal distribution with mean zero. In order to facilitate the determination of constants and parameters, the mathematical models were linearized by performing logarithmic transformation as follows:

$$\ln T = \ln C + n \ln V + m \ln S_0 + \ln \in \text{..................}(2)$$

This linear model in terms of the estimated response can be written as:

$$\hat{y} = y - \in = b_0 x_0 + b_1 x_1 + b_2 x_2 \text{.....................}(3)$$

where $\hat{y}$ is the estimated response on a logarithmic scale, y is the measured response on a logarithmic scale, $x_0 = 1$ (dummy variable), $x_1 = \ln V, x_2 = \ln S_0$, $\in$ is the experimentally random error and the b values are the estimates of the model parameters to be estimated. According to equation (3) process, tool life model can be represented by the following equations respectively:

$$\ln T = \ln C + n \ln V + m \ln S_0 + \ln \in \text{.............................}(4)$$

The significance of these variables is judged by statistical analysis. In the present study, the parameters of equation (4) have been estimated by the least-square method using a Minitab computer package.

Montgomery [12] explains the details for formulating a first order model for employing first order model. To develop the first-order model, a design consisting of seven experiments was selected. Four experiments constitute 2^2 factorial designs with an added centre point repeated three times, the added centre point being used to estimate pure error. The design provides three levels for each of the independent variables. Table 1 shows the levels of the independent variables and coding identifications. The experimental cutting conditions together with the measured surface roughness values are presented in Table 2.

Table 1: Levels of the independent variables

Levels	Low	Centre	High
Coding	-1	0	+1
Speed (m/min)	133	186	266
Feed (mm rev)	0.14	0.18	0.22

Table 2: Experimental conditions and results

Trial	Speed (m/min)	Feed (mm/rev)	Coding		Tool Life T (mins)
			X1	X2	
1	133	0.14	-1	-1	90
2	133	0.22	-1	1	60
3	266	0.14	1	-1	30
4	266	0.22	1	1	14
5	186	0.18	0	0	56
6	186	0.18	0	0	54
7	186	0.18	0	0	55

The transforming equations for each of the independent variables are as follows:

$$
\begin{aligned}
x_1 &= \frac{\ln V - \ln 133}{\ln 266 - \ln 133} \\
\Rightarrow x_1 &= 1.443 \ln V - 7.055 \\
x_2 &= \frac{\ln S_0 - \ln 0.14}{\ln 0.22 - \ln 0.14} \\
\Rightarrow x_2 &= 2.212 \ln S_0 + 4.35
\end{aligned}
\qquad \text{......................................} (5)
$$

2.2 Test procedure

The machining tests have been carried out by straight turning of medium carbon steel on a lathe (10 hp: China) by standard uncoated carbide insert at different cutting velocities (V) and feeds (So) and constant depth of cut (t) under dry and high pressure coolant conditions. The experimental conditions have been given in Table-3. Effectiveness of cooling and the related benefits depend on how closely the high pressure coolant jet can reach the chip-tool and the work-tool interfaces where, apart from the primary shear zone, heat is generated. The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping this view tool configuration namely SNMG-120408 has been undertaken for the present investigation. The insert was clamped in a PSBNR-2525 M12 type tool holder. The positioning of the nozzle tip with respect to the cutting insert has been settled after a number of trials. The high-pressure coolant jet is directed along the auxiliary cutting edge at an angle 30^o to reach at the principal flank and partially under the flowing chips through the in-built groove parallel to the cutting edges. A cylindrical bar of medium carbon steel of 173 mm diameter was selected for straight turning. During machining, the cutting insert was withdrawn at regular intervals and then VB is measured under metallurgical microscope (Carl Zesis, 351396, Germany) fitted with micrometer of least count 1μm. The readings were taken until tool life criterion was reached.

Table 3: Experimental conditions

Machine tool	: Lathe Machine (China) 10hp
Work material	: Medium carbon steel (φ173 X 710 mm)
Cutting tool	
Cutting insert	: SNMG 120408 TTR
Tool holder	: PSBNR 2525M12
Working geometry	: -6^o,-6^o,6^o, 15^o, 75^o, 0.8 (mm)
Process parameters	
Cutting velocity	: 133, 186 and 266 m/min
Feed rate	: 0.14, 0.18 and 0.22 mm/rev
Depth of cut	: 1.0 mm
High-pressure coolant	: 70 bar, Coolant: 6.0 l/min through external nozzle
Environments	: Dry and High-pressure coolant

3. RESULTS AND DISCUSSION

The postulated model for tool life based on 7 set of experiments is-

$$\hat{y} = 1.09-1.04 x_1-1.01x_2 \quad \text{..}(6)$$

Using equation (6), the tool life model can be transformed using eq. (5) into the following form:

$$T= 9.13 \times 10^3 V^{-1.92} S_0^{-2.7} \quad \text{..}(7)$$

This equation indicates that under high-pressure coolant condition, the tool life decreases with increase of cutting speed and feed. The feed has the most significant effect on the tool wear. Equation (7) is plotted in Fig. 1 as the response surface of for different combinations of cutting speed and feed.

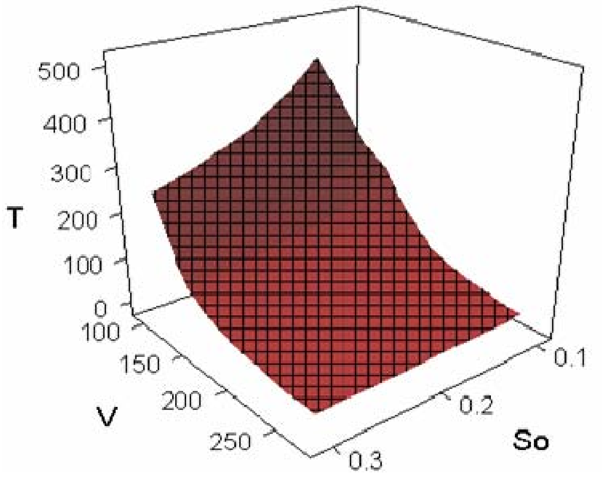

Fig 1: Tool Life as a Function of cutting speed and feed

Table 4: Analysis of Variance for Tool Life

Sources of Variation	**Sum of Squares**	**DF**	**Mean Squares**	**F_{cal}**	**F_{tab}**
Regression	0.33014	2	0.16507	1.523[a]	7.71
Residual	0.43336	4	0.10834		
Interaction	0.04240	1	0.04240	0.994	18.51
Pure quadratic	0.30565	1	0.30565	7.166	18.51
Pure error	0.0853	2	0.04265		
Total		6			

[a] significant at 5%.

The analysis of variance as shown in Table-4 proves the adequacy of the model as the regression effect is dominant in relation to curvature and interaction effects. However, the presence of quadratic and interaction effect justifies development of higher order model. The pure quadratic effect is higher than interaction effect. So, effect of quadratic may be considered to obtain better fitted model. A number of experiments were carried out to substantiate the validity of the model.

Table 5: Comparison between predicted and measured values of tool wear

Expt No	Speed m/min	Feed mm/rev	Tool Life, T, min		
			Predicted	Measured	Error
1	133	0.18	78.2	68	15%
2	186	0.14	81	70	16%
3	186	0.22	36.9	40	-8%
4	266	0.18	20.7	18	15%

Table-5 presents the predicted results obtained from the models and actual results obtained from the experiments. It also shows the percentage deviation of the predicted value from the model values. Table-5 shows that, the tool life model predicts the model quite fairly as the maximum error is 16% which is reasonably acceptable. So, both the model can be used to estimate the performances reasonably correctly. The correlation between the values obtained from measurement and proposed model for tool life and surface roughness have been depicted in Fig. 2

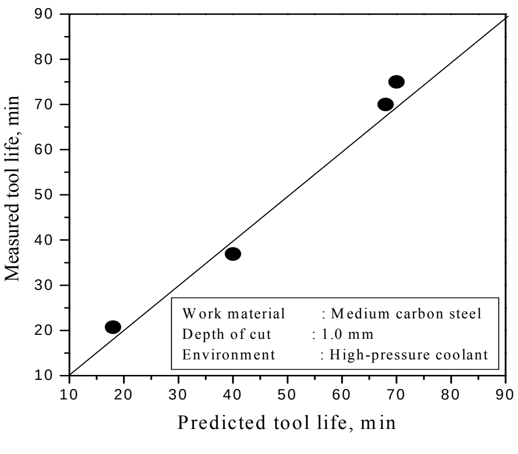

Fig 2: Comparison of measured and predicted tool life

4. CONCLUSION

(1) First-order tool life prediction equations have been developed from the factorial design of experiments. As part of applying response surface method, regression analysis was employed to find the parameters so that proposed first order model to fit experimental results. This was followed a performing analysis of variance, ANOVA, the adequacy of the model was verified

(2) ANOVA also shows that the interaction between the independent variables are insignificant compared the regression effect. However, as the ANOVA table indicates the presence of quadratic and interaction, though in small amount, a second or higher model may be employed in development of statistical model.

(3) The results have revealed that the effect of feed is much more pronounced than the effects of cutting speed and depth of cut, on the surface roughness.

(4) A subsequent second set of tests were carried out to measure the deviation between the predicted and actual machining performance. This experimentation shows that the tool life model can also be considered to predict tool life. The amount of error is 16% at best which can be considered to be reasonable and the model can be considered accurate.

(5) Response surface methodology coupled with the factorial design of experiments is a better alternative than the traditional one-variable-at-a-time approach. This provides a large amount of information with a lesser number of experiments.

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