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DEVELOPMENT OF TOOL LIFE PRDICTION MODEL FOR PCBN INSERTS DURING THE HIGH SPEED END MILLING OF AISI H13 HARDENED TOOL STEEL

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ABSTRACT

This paper presents the result of an experimental investigation on tool wear of PCBN tool insert during the high speed end milling of AISI H13 tool steel under dry cutting condition. Sufficient numbers of experiment were run based on the central composite design (CCD) concept of response surface methodology (RSM) in order to generate tool life data. An empirical second order quadratic model in terms of cutting speed, feed and axial depth of cut has been developed for the effective prediction of tool life under particular cutting condition. The adequacy of the model has been verified by ANOVA at 95% confidence interval. From the model it is clear that cutting speed possesses the most dominating effect over tool life followed by feed and axial depth of cut. An increasing cutting speed, feed and axial depth of cut will result in decreasing tool life.

Keywords: Tool life, PCBN tool insert, AISI H13 tool steel, RSM.

1. INTRODUCTION

The machining of steels at their hardened state was prevalently adopted during the last decade. Hard machining, a widely used term now a days, refers to the direct machining of material with a hardness value over 45 HRC. Considering the demand for reduced cycle time and increased productivity hard turning and milling have become a useful alternative when high material removal rate is an immense requirement. Advantages in hard machining incorporate the complete machining process with a single fixture setup, eliminating intermediate heat treatment and final grinding process while still meeting the dimensional and surface roughness specifications [1]. The preliminary development had been initiated with turning operation to replace cylindrical grinding, and the later work was on milling using a ball end mill at high speed cutting [2].

Because of it's high hardness, thermal stability and wear resistance property, Polycrystalline boron nitride (PCBN) is the major class of tool material for high speed machining of hardened steel like AISI H13 [3]. In fact, hard machining concept has been accelerated with the advent of new improved PCBN tools. However, PCBN tool is still vulnerable due to rapid flank wear, thermal fatigue and catastrophic failure at high cutting speed in intermittent cutting application. Early prediction of tool wear during high speed machining by CBN tool is quite important since high tool wear has an adverse effect on surface finish, which is considered to be the major quality criterion of finished part. Moreover, the recent approaches of designing a suitable data selection system for computer integrated manufacturing (CIM) application considers machinability database systems in the form of mathematical modeling which has considerable advantage over simple data retrieval system [4-5]. In this context, in the present study, an appropriate model for effective prediction of tool life has been developed during the high speed end milling of H13 tool steel using PCBN tool inserts.

2. LITERATURE SURVEY

Over the last decade high speed machining has been used extensively to produce mould and die from hardened material like AISI H13 tool steel. Many progressive works have been carried out to improve the high speed machining performance of H13. Despite the widespread adoption of milling process in fabricating mould and die, most of the research works till to date concentrated on hard turning.

Junz Wang et al.[1] compared the machining characteristics of AISI H13 tool steels of hardness 41 and 20 HRC during the ball end milling by solid carbide tool insert. They illustrated the machining characteristics through the milling force, the chip form, and the surface roughness. Poulachon et al. [6] showed that the major influencing parameter on tool-wear happens to be the presence of carbides in the steel microstructure. König et al. [7] found that tool life can vary in a very wide range for different hardened steels, heat treated to same hardness and machined under the same cutting conditions. Ghani et al. [8] applied Taguchi method to optimize cutting parameters in end milling of H13 steel at high speed cutting. They found that feed and depth of cut possess the most significant effect over tool life for a given range of cutting speed, feed and depth of cut. The effect of cutting speed was found to be less significant within their tested zone. In another consecutive study Ghani et al. [9] showed the flank wear progression in case of P10 TiN coated carbide tools. Fallbohmer et al. [10] evaluated the cutting technology during the high speed milling of H13 at 46 HRC, P-20 at 20±40 HRC and cast iron by carbides, coated carbides, and PCBN. They emphasized various aspects of machining including machine tool, tool holder, spindle rigidity; controllers and NC programming; reliability and process knowledge and process modeling.

The current study utilized response surface methodology (RSM) to predict the tool life. RSM is a statistical method that combines design of experiments, regression analysis and statistical inferences. It is a very useful technique for the modeling and analysis of problems in which a response of interest is influenced by several variables; where the objective is to optimize this response [11]. RSM also reduces total number of trials needed to generate the experimental data in order to response model.

The application of RSM in machining parameter optimization was first reported to be used by SM.Wu [12]. Since then many researchers have been using this technique to design their experiments and model the responses. Kuang-Hua Fuh and Chih-Fu Wu [13] used RSM for surface quality prediction in end milling of Al alloy. Beside the usual cutting variables, they considered nose radius and flank width as parameters to be optimized for better surface quality. Alauddin et al. [14] used RSM to optimize the surface finish in end milling of Inconel 718 under dry condition. They developed contours to select a combination of cutting speed, and feed without increasing the surface roughness. Öktem et al. [15] incorporated RSM with developed genetic algorithm to optimize cutting parameters for better surface quality in case of Inconel718. Saikumar et al. [16] also combined RSM with differential evolution and genetic algorithms to draw a comparison between these methods.

In the present work, a 2nd order model was developed by RSM in terms of cutting speed (v), feed (f) and axial depth of cut (a). Experimental runs were designed based on the principles of central composite design (CCD) of RSM. Tool life data collected from the experimental trials were used to formulate the RSM models

3. METHODOLOGY

3.1 Mathematical Model Formulation

The tool life (T) can be correlated with cutting speed (v), axial depth of cut (a) and feed (f) by the following empirical equation:

$$TL = C\, v^k a^l f^m \tag{1}$$

Here, *'C'* is a model constant and *k*, *l* and *m* are the model parameters. Eq. (1) can be represented in linear form by using natural logarithm, which is as follows

$$Ln(TL) = lnC + klnv + l\, lna + m\, lnf \tag{2}$$

The first-order linear model of Eq. (2) can be represented as follows

$$\hat{y}_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \tag{3}$$

Where, $\hat{y}$ is the estimated response based on first-order equation and y the measured surface roughness on a logarithmic scale; $x_0 = 1$(dummy variable), x_1, x_2, x_3 are logarithmic transformations of speed, axial depth of cut and feed respectively; while b_0, b_1, b_2, and b_3 are the parameters to be estimated and ε is the experimental error.

The second-order model can be extended from the first-order model's equation like as follows:

$$\hat{y}_2 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \tag{4}$$

Where, $\hat{y}_2$ denotes the estimated response based on the second-order model. This second order response equation considers the influence of single factor along with their quadratic as well as interactive effects over the response.

3.2 Coding of the Independent Variables

The cutting conditions were selected considering the recommendations of PCBN tool manufacturer (Sandvik Tools). Few trial runs were also conducted to substantiate the selection of parameters. The three main selected parameters- cutting speed, axial depth of cut and feed were coded taking into consideration the limitation and capacity of the cutting tools. Levels of independent and coding identification are presented in Table 1.

Table 1: Coding identification of independent variables

Levels	*Lowest*	*Low*	*Center*	*High*	*Highest*
Coding	$-\sqrt{2}$	-1	0	+1	$+\sqrt{2}$
x_1,cutting speed,(m/min)	400.05	434.2	529.21	645.00	700.06
x_2, axial depth of cut, (mm)	1.00	1.17	1.73	2.55	3.00
X_3, feed (mm/tooth)	0.05	0.06	0.09	0.013	0.15

The transforming equations for each of the independent variables are:

$$x_1 = \frac{\ln V - \ln 529.21}{\ln 645.00 - \ln 529.21}$$
$$x_2 = \frac{\ln a - \ln 1.73}{\ln 2.55 - \ln 1.73}$$
$$x_3 = \frac{\ln f - \ln 0.09}{\ln 0.13 - \ln 0.09} \tag{5}$$

Table 2: Cutting condition and tool life result

Std. order	Location in CCD	Coded form			Actual Form			Response
		X_1	X_2	X_3	Cutting speed (m/min)	Depth of cut (mm)	Feed (mm/tooth)	Tool life (min)
1	Factorial	1	1	-1	185.7	2.55	0.06	5.75
2	Factorial	1	-1	1	185.7	1.17	0.013	3.85
3	Factorial	-1	1	1	129.4	2.55	0.013	7.81
4	Factorial	-1	-1	-1	129.4	1.17	0.06	18.13
5	Center	0	0	0	155.01	1.73	0.09	7.6
6	Center	0	0	0	155.01	1.73	0.09	7.8
7	Center	0	0	0	155.01	1.73	0.09	8.96
8	Center	0	0	0	155.01	1.73	0.09	8.96
9	Center	0	0	0	155.01	1.73	0.09	9
10	Axial	$-\sqrt{2}$	0	0	120.08	1.73	0.09	25.82
11	Axial	$+\sqrt{2}$	0	0	200.08	1.73	0.09	2.09
12	Axial	0	$-\sqrt{2}$	0	155.01	1	0.09	16.04
13	Axial	0	$+\sqrt{2}$	0	155.01	3	0.09	3.6
14	Axial	0	0	$-\sqrt{2}$	155.01	1.73	0.05	15.9
15	Axial	0	0	$+\sqrt{2}$	155.01	1.73	0.15	3.46

3.3 Experimental Details

Experimental trials were performed on CNC Vertical Machining Center (VMC), model no. Excell PMC-10T24, using a 40 mm diameter tool holder equipped with a single tool insert. End milling operations were performed under dry cutting conditions considering 5 mm constant radial depth of cut. Down milling method was employed to enhance better surface finish, less heat generation, larger tool life, better geometrical accuracy and compressive stresses favorable for cutting tool edges.

The types of cutting tools were selected from the SANDVIK Coromant tool catalogue. After every 50 mm length of cut, tool wear was measured using Hisomet III tool maker microscope of model OH II-7178 using a magnification of 20X.

Small CCD with 5 levels was selected to design the experiments which results in 15 experiments including 5 center-runs. The analysis of mathematical models was carried out using Design-expert 6.0.8 package. Cutting conditions both in coded and actual form are presented in Table 2.

4. RESULT & DISCUSSION

Tool lives obtained from different experimental runs are presented in the last column of table 2. The analysis of variance table (ANOVA table) for tool life of PCBN tool insert is shown in table 3. This table presents each of the estimated effects, along with their interactions and standard error, which is used for measuring the sampling error. The purpose of ANOVA table is to assess the statistical significance of each factor by comparing the mean square against the estimate of experimental error. In this case, x_2^2 and x_1x_3 have P-values higher than 0.05, indicating that they are insignificant at 95% confidence interval. Too many insignificant model terms may result in significant lack of fit.

Table 3: ANOVA for response surface quadratic model

Source	SS	DF	MS	F ratio	P-value
X_1	2.054	1	2.054	5257.66	< 0.0001
X_2	0.454	1	0.454	1163.35	< 0.0001
X_3	0.484	1	0.48478	1240.48	< 0.0001
X_1^2	0.049	1	0.049	125.705	0.0004
X_2^2	5.72E-05	1	5.72E-5	0.1464	0.7215
X_3^2	0.057	1	0.0567	145.231	0.0003
$X_1 X_2$	0.056	1	0.056	142.943	0.0003
$X_1 X_3$	2.4 E-4	1	0.00024	0.6255	0.4733
$X_2 X_3$	0.078	1	0.0784	200.707	0.0001
Pure Error	1.56 E-3	4	0.0004		

That's why, x_2^2 and x_1x_3 can be discarded, for a better fit quadratic model.

The ANOVA table for reduced quadratic model is given by table 4. This table comprises the P value for proposed 2nd order model and the lack of fit. As it is seen from the table, the model's F value is 2205.71 resulting in P value of less than 0.0001. It justifies that the model is significant for the prediction of tool wear. There is at best 0.01% chance that a "Model F-Value" this large could occur due to noise. The lack of fit test denotes whether the selected model is adequate to describe the observed data or a more complicated model is required to be used. Here, the lack of fit is insignificant for having a P-value higher than 0.05

Table 4: ANOVA for reduced quadratic model

Source	SS	DF	MS	F value	Prob > F
Block	0.017	1	0.017		
Model	4.8	7	0.685	2205.714	< 0.0001
x_1	2.05	1	2.05	6610.793	< 0.0001
x_2	0.94	1	0.94	3022.219	< 0.0001
x_3	0.484	1	0.4847	1559.738	< 0.0001
X_1^2	0.0491	1	0.0491	158.0001	< 0.0001
x_3^2	0.057	1	0.0572	184.0527	< 0.0001
x_1x_2	0.056	1	0.0558	179.7313	< 0.0001
x_2x_3	0.078	1	0.07843	252.3615	< 0.0001
Residual	0.0018	6	0.000311		
Lack of Fit	0.0003	2	0.00015	0.385945	0.7026
Pure Error	0.0016	4	0.0004		
Cor Total	4.82	14			

The adjusted quadratic model for the prediction of tool wear is shown by Eq. (6):

$$ln\ (TL) = 2.57 - 0.716\ x_1 - 0.342\ x_2 - 0.348\ x_3 - 0.08\ x_1^2 - 0.087\, x_3^2 - 0.167\, x_1x_2 - 0.198x_2\, x_3 \tag{6}$$

In Eq. (6) the cutting speed, axial depth of cut and feed have been expressed in terms of their logarithmic transformations. Since all the three parameters are under the same logarithmic scale, the factor with the highest value of coefficient possesses the most significant effect over the response (logarithm of tool life). In this respect as it is seen from the model, cutting speed has the most dominating effect over tool life, followed by feed and axial depth of cut. An increasing cutting speed will result in decreasing tool life, which is also common in case of feed and axial depth of cut. Tool life is also greatly influenced by the interaction between feed and axial depth of cut and the interaction between cutting speed and feed.

Fig. 1 and 2 show the logarithmic tool life as the function of x_1 and x_2, for the minimum and maximum value of x_3; here, x_1, x_2 and x_3 denote the logarithmic transformation of cutting speed, axial depth of cut and feed respectively. The response surface plot is a good tool to estimate the region of maximum tool life, which is basically similar to the 3-D wire frame plot [17]. As it is observed from Fig. 1 and 2, tool life decreases as the cutting speed or axial depth of cut increases. Comparing the two figures it is also apparent that for higher value of feed we may get a lower value of tool life. The findings from the experiment is quite obvious, which keeps a good pace with others works so far been studied on tool life in hard milling. High cutting speed imposes higher amount of force over cutting edge and generate higher amount of temperature, which ultimately shorten the tool life. High mechanical impact caused by increasing feed and axial depth of cut also results in decreasing tool life.

The Eq. (6) is valid for end milling of H13 tool steels under dry condition with 5 mm radial depth of cut using PCBN tool inserts with the following range of cutting speed *V*, feed *f,* and axial depth of cut, *a:* 434.20 m/min ≤ V ≤ 645.00 m/min, 1.17 mm ≤ a ≤ 2.55 mm, and 0.06 mm/tooth ≤ f mm/tooth ≤ 0.13 mm/tooth, respectively.

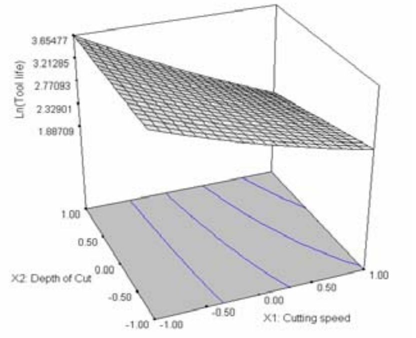

Fig 1: Logarithm of tool life as the function of x_1 and x_2, for minimum value of x_3

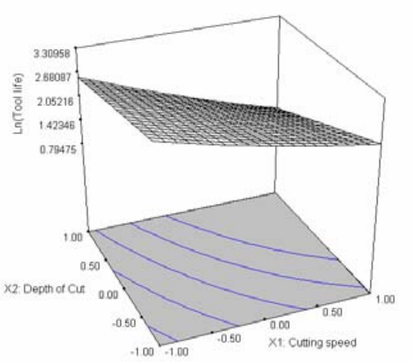

Fig 2: Logarithm of tool life as the function of x_1 and x_2, for minimum value of x_3

5. CONCLUSIONS

This paper presents an experimental investigation on tool life of PCBN tool insert during high speed end milling of H13 tool steel. Based on the central composite design concept of response surface methodology sufficient numbers of experiments were performed to generate the tool life data. These results were used to develop a second order quadratic model for the prediction of tool life of PCBN tool insert. The general conclusions from the current study can be summarized as follows:

1. Response surface methodology has been proven to be an efficient method for predicting the tool life during end-milling of H13 tool steel using PCBN tool inserts under dry cutting conditions. A second order prediction model has been developed for a given range of cutting speed, axial depth of cut and feed, which is valid with in the range of cutting speed 129.4 m/min to 185.7 m/min; axial depth of cut 1.17 mm to 2.55 mm; and feed 0.06 mm/tooth to 0.13 mm/tooth.
2. The model is adequate under 95% confidence interval, with sufficient value of fit.
3. Cutting speed is found to have the most significant

effect over tool life, followed by feed and axial depth of cut. An increasing of cutting speed, feed and axial depth of cut will result in decreasing tool life.

4. The interaction between feed and axial depth of cut and the interaction between cutting speed and feed also have significant effect over tool life

6. NOMENCLATURE

Symbol	Meaning	Unit
TL	Tool life	(min)
v	Cutting speed	(m/min)
a	Axial depth of cut	(mm)
f	Feed	(mm/tooth)
x_1	Logarithmic transformation of cutting speed	
x_2	Logarithmic transformation of axial depth of cut	
x_3	Logarithmic transformation of feed	
SS	Sum of square	
DF	Degree of freedom	
MS	Mean square	

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