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Tool Life Modeling in High Speed Turning of AISI 4340 Hardened Steel with Mixed Ceramic Tools by Using Face Central Cubic Design

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Abstract – *Tool life estimation for the cutting tool before the machining process is important due to economic and quality consideration. Thus, developing a model that can predict the tool life with high accuracy is an important issue. This paper deals with developing a new model of tool life for mixed ceramic tools in turning hardened steel AISI 4340 based on experimental tests. The experiments were planned and implemented using Central Composites Design (CCD) of Response Surface Methodology (RSM) with three input factors: cutting speed, feed rate and negative rake angle. The Face Central Cubic Design has been used as a special case of CCD. The analysis of variance (ANOVA) has been conducted to analyze the influence of process parameters and their interaction during machining. The first and second order models have been developed. It was found that the second order model provide higher accuracy prediction than the first order model. It was observed that the cutting speed is the most significant factor that influences the tool life for the two models, followed by the feed rate then the negative rake angle. The predicted values are confirmed by using validation experiments.* ***Copyright © 2013 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords: *Tool Life, High Speed Hard Turning, Mixed Ceramic, FCC*

I. Introduction

The prediction and detection of tool wear before the tool cause any damage to the final surface becomes highly valuable in order to avoid loss of product, damage to the machine tool and associated loss in productivity [1]. In high speed hard turning, the cutting area is under high temperature, high pressure, and high sliding velocity [2]. Therefore, the cutting tool under this condition has normally complex wear behaviors.

Mamalis et al. [3] claimed that with the change of cutting conditions, the tool's mechanical and thermal load changes, and the ratio of the wear components modifies.

Therefore, it is difficult to handle mathematically. Tool life has been defined as the usable time that has elapsed before the criterion value of flank wear is reached [4].

Many researchers [5]-[20] used and compared between different methods for modeling the tool life or the flank wear such as the regression analysis techniques and the neural network techniques in predicting the tool life for different turning process.

In this research, the face central cubic (FCC) has been used for modeling the tool life. Also, the recommendation in ISO 3685 [21] was considered. The cutting tool tip was cleaned with compressed air and alcohol prior to taking any measurement. The tests were carried out using tool life criteria of average flank wear equal to 0.3 mm.

Tool life is determined according to the following equation [22]:

$$L = VB / r_w \quad (1)$$

$$r_w = \Delta VB / \Delta t \quad (2)$$

where L is the tool life (min), VB is the maximum flank length (μm), t is the machining time (min) and is the flank wear rate (mm/min).

Turning operation was continued until average VB of 0.3 mm.

An average of 0.3 mm was used as a criterion to determine the tool life by calculating the progress wear rate and the machining time as shown in Fig. 1.

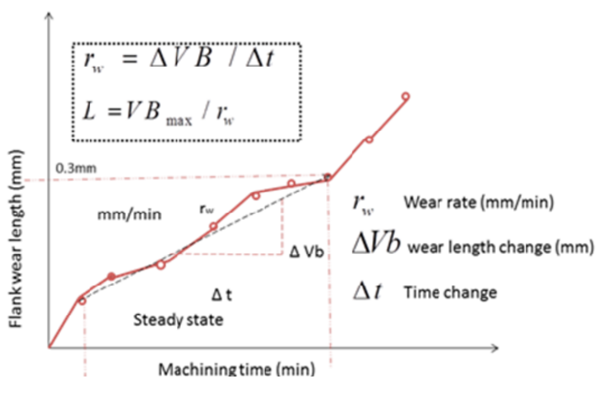

Fig. 1. Tool life estimation by using regression analysis

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II. Modeling

A mathematical model is a description of a system using mathematical language. This process termed mathematical modeling while the optimization issue is how to find the setting of the input parameters to the model to optimize all the output responses simultaneously [23].

Mukherjee and Ray [24] classified the modeling techniques into three main parts: statistical regression [25], artificial neural network [26] and fuzzy set theory [27]. The multi statistical regression technique is a simple and accurate technique to investigate the functional relationship between the different inputs and outputs.

Different designs can be applied to investigate and modeling the machining parameters such as central composite design and Box Behnken Design. In this research the Face Central cube (FCC) has been applied to develop a new model of tool life.

II.1. Central Composite Design (CCD)

A Central Composite Design (CCD) is a fractional design with center points that is augmented with a group of star points [28].

The CCD is built up from; two level factorial design plus center point and axial points represented by stars plus more center points [25].

This design varied over five levels in axial points except the face centered cube which can run only with three levels. Fig. 2 shows the different designs in the CCD; Central Composite Circumscribed (CCC), Central Composite Inscribed (CCI), and face central cube (FCC).

These axial points go outside of the factorial box. This has advantages and disadvantages. It's good to go further out for assessing curvature, but it may be inconvenient for the experimenter to hit the five levels required of each factor: low axial (star at smallest value), low factorial, center point, high factorial, and high axial (star at greatest value) [27].

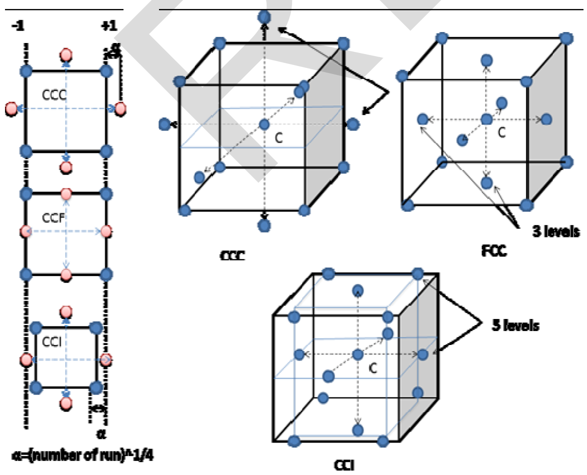

Fig. 2. Central composite design (CCD)

II.2 Face Central Cube

In many situations, the region of interest is cubical rather than spherical. In these cases, a useful variation of the central composite design is the face-centered central composite design or the face centered cube (FCC) [29].

Face Centered Cube design is one of the special cases in CCD where the experiment can be done in three levels as shown in Fig. 2.

This design locates the star or axial points on the centers of the faces of the cube. This design is also sometimes used because it requires only three levels of each factor.

III. Experimental Design

AISI 4340 hardened steel was selected as work piece due to its several and widespread application. The material was hardened to 60 HRC. The insert chosen for this study was CC650 from sandvik products. It is mixed ceramic grade based on alumina with an addition of (30%) titanium carbide.

It is primarily recommended for finishing operations in hardened steel where the combination of wear resistant and good thermal properties is required. FCC has been used in developing the tool life models in first and second order model as shown in Table I with fix depth of cut on 0.15 mm.

TABLE I
FACE CENTRAL CUBIC DESIGN

	L1	L2	L3
Cutting speed m/min	175	250	325
Feed rate mm/rev	0.075	0.1	0.125
Rake angle degree	0	-6	-12

The first-order model and second-order model have been developed by an experimental design consisting of 15 experiments in addition to five central points as shown in Table II.

TABLE II
EXPERIMENTAL DATA

No of Run	Cutting Speed (m/min)	Rake angle (degree)	Feed rate (mm/rev)	Tool life (min)
1	175	-12	0.075	14.139
2	175	0	0.075	12.882
3	175	-6	0.1	9.842
4	175	-12	0.125	6.237
5	175	0	0.125	5.769
6	250	-6	0.075	8.783
7	250	-12	0.1	5.319
8	250	-6	0.1	5.681
9	250	-6	0.1	5.681
10	250	-6	0.1	5.681
11	250	-6	0.1	5.681
12	250	-6	0.1	5.681
13	250	-6	0.1	5.681
14	250	0	0.1	4.528
15	250	-6	0.125	3.798
16	325	-12	0.075	5.434
17	325	0	0.075	4.764
18	325	-6	0.1	3.869
19	325	-12	0.125	2.097
20	325	0	0.125	1.864

III.1. Tool-Life Model

The design of expert software (DOE 6) was used for analyzing the output data. Analysis of variance (ANOVA) was conducted on the suggested and modified models. In both designs, the probability values in the ANOVA Tables were lower than 0.05 as shown in Tables III and IV; hence, there is a statistically significant relationship between the variables at the 95% confidence level.

TABLE III
ANALYSIS OF VARIANCE (ANOVA) TABLE
FOR THE FIRST ORDER MODEL

Response	Tool life					
Source	sum of squares	df	mean square	F value	p-value > F	
Model	175.0121	6	29.16869	51.04186	<0.0001	Significant
A	95.09995	1	95.09995	166.414	<0.0001	
B	1.168207	1	1.168207	2.044229	0.1764	
C	68.83864	1	68.83864	120.4597	<0.0001	
Ab	0.084349	1	0.084349	0.147601	0.7070	
AC	9.633115	1	9.633115	16.85685	0.0012	
BC	0.18771	1	0.187881	0.328771	0.5762	

A: cutting speed, B: rake angle, C: feed rate

TABLE IV
ANALYSIS OF VARIANCE (ANOVA) TABLE
FOR THE SECOND ORDER MODEL

Response	Tool life					
Source	sum of squares	df	mean square	F value	p-value > F	
Model	182.3502	9	20.26113	2226.298	<0.0001	Significant
A	95.09995	1	95.09995	10449.6	<0.0001	
B	1.168207	1	1.168207	128.3629	<0.0001	
C	68.83864	1	68.83864	7564.005	<0.0001	
AB	0.084349	1	0.084349	9.268297	0.0124	
AC	9.633115	1	9.633115	1058.489	<0.0001	
BC	0.187881	1	0187881	20.64446	0.0011	
A^2	3.655739	1	3.655739	401.6934	<0.0001	
B^2	1.669664	1	1.669664	183.463	<0.0001	
C^2	0.950191	1	0.950191	104.4072	<0.0001	

A: cutting speed, B: rake angle, C: feed rate

The R^2, adjusted R^2 are high and very close to each other besides the increasing of the predicted R^2 after the elimination of the insignificant terms as shown in Table V, therefore the models are reliable for prediction the different factors. Furthermore, the signal to noise ratio for the quadratic and the modified models for tool life models were more than 4, therefore the different models indicates an adequate signal. Thus, the modified second order quadratic models can be used to navigate the design space as shown in the following equations:

$$L\ (2^{nd}\ \text{order}) = 61.24 - 0.206\,V_c - 0.476\,R + \\ -433.23\,f + 2.28e^{-4}\,V_c R + 0.585\,V_c f + 1.022 \\ Rf + 2.0e^{-4}\,V_c^2 - 0.022\,R^2 + 940.501\,f \quad (3)$$

$$L\ (1^{st}\ \text{order}) = 41.575 - 0.099642\ V_c \\ -251.26\ f + 0.585\ V_c f \quad (4)$$

The results was validated and gives a deviation equal to 1.4% for the second order model and 11.8% for the first order model as shown in Fig. 3 and Fig. 4.

The perturbation plot for the two models showed that the cutting speed is the most significant factor on tool life as shown in Fig. 5 and Fig. 6.

TABLE V
R-SQUARED

Factor	1st order	2nd order
R-Squared	0.95928	0.999501
Adjusted R-Squared	0.94048	0.999052
Predicted R-Squared	0.82544	0.994831
Adequate Precision	27.0525	179.3544

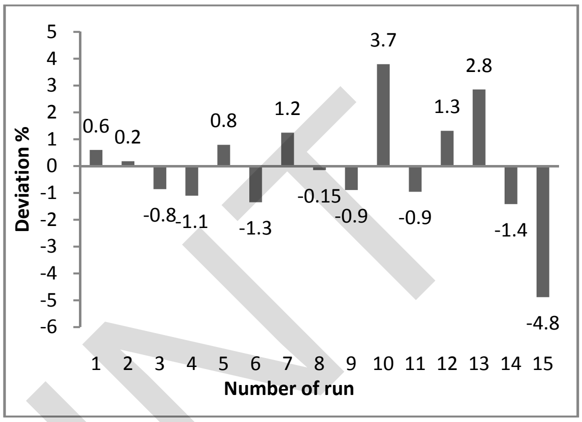

Fig. 3. 2nd order deviation

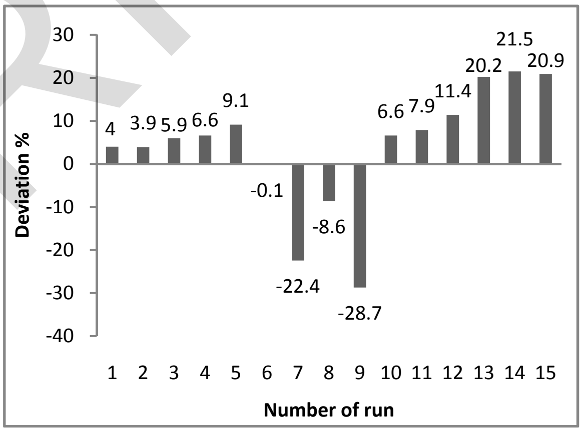

Fig. 4. 1st order deviation

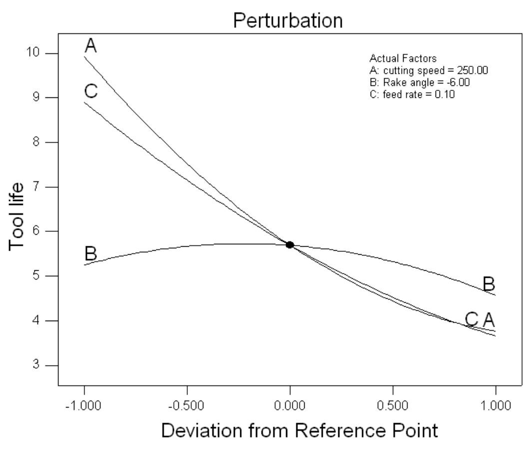

Fig. 5. Perturbation Plot for the first order model

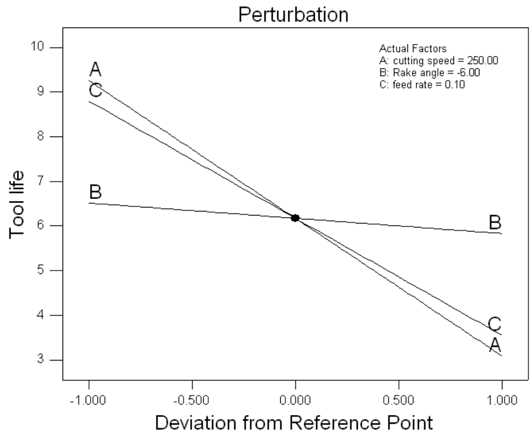

Fig. 6. Perturbation Plot for the second order mode

IV. Conclusion

1. Regression analysis has been successfully used to develop the predict tool life models.
2. Even though the 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.
3. Second order model gives better accuracy than first order model design because second order model contains the more significant terms.

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