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Full Length Research Paper

Prediction of tool life by statistic method in end-milling operation

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The aim of the this study is to develop the tool life prediction model for P20 tool steel with aid of statistical method, using coated carbide cutting tool under various cutting conditions. This prediction model was then compared with the results obtained experimentally. By using Response Surface Method (RSM) of experiment, first and second order models were developed with 95% confidence level. The tool life was developed in terms of cutting speed, feed rate, axial depth and radial depth, using RSM and design of experiment. In general, the results obtained from the mathematical model are in good agreement with that obtained from the experiment data's. It was found that the feedrate, cutting speed, axial depth and radial depth played a major role in determining the tool life. On the other hand, the tool life increases with a reduction in cutting speed and feedrate. For end-milling of P20 tool steel, the optimum conditions that is required to maximize the coated carbide tool life are as follow: cutting speed of 140 m/s, federate of 0.1 mm/rev, axial depth of 1.5 mm and radial depth of 2 mm. Using these parameters, a tool life of 39.46 min was obtained.

Key words: End-milling, tool life, response surface method.

INTRODUCTION

The life of a tool is important in metal cutting since considerable time is lost whenever a tool is replaced or reset. Cutting tools loose it's sharpness as usage continues and their effectiveness decrease over time. At some point during the life-span of the tool, it is necessary to replace, index or resharpen and reset the tool. Tool life is a measure of the length of time a tool will cut effectively. The life of cutting tool depends upon many factors, such as the microstructure of the material being cut, metal removal rate, the rigidity of the setup and effects of cutting fluid (David and Agapiou, 2000; Krar, 1995). The correct choice of cutting velocity can enhance tool life but at the same time, the tool should be used to its maximum capacity. From the research published by Sharman (2001), the tool coating was found to be the main factor affecting tool life followed by cutting speed and workpiece angle. According to Alauddin et al. (1997), an increased in the cutting speed, feedrate and axial depth of cut would decrease the tool life.

Response Surface Method (RSM) saves cost and time on conducting metal cutting experiments by reducing the overall number of required tests. In addition, RSM helps describe and identify, with a great accuracy, the effect of the interactions of different independent variables on the response when they are varied simultaneously (Mead and Pike, 1975; Hill and Hunter, 1966; Hicks, 1993). RSM has been extensively used in the prediction of responses such tool life, surface roughness and cutting forces. Up-to-date, few researches used RSM to study the effect of cutting conditions on cutting forces when end-milling of tool steels used to produce plastic injection moulds such as modified AISI P20 steel.

In this study, the tool life developed when end-milling of modified AISI P20 tool steel is investigated using res-

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Table 1. Levels of independent variables.

Factors \ Coding of Levels	-1	0	1
Speed, V_c (m/s)	100	140	180
Feed, f (mm/rev)	0.1	0.2	0.3
Axial depth of cut, a_a, (mm)	1	1.5	2
Radial depth of cut, a_r, (mm)	2	3.5	5

ponse surface method. The first and second predictive models are developed for four cutting conditions: feed rate, cutting speed, axial depth of and radial depth of cut. The received quadratic equation shows, as a result of the variance analysis, that the most influential input parameter was the feedrate, followed by the cutting speed, axial depth and radial depth. In addition, the interactions of radial depth of cut together with feed; and radial depth of cut with axial depth of cut were observed to be quite significant. The predictive models in this study are believed to produce values of the longitudinal component of the cutting force close to those readings recorded experimentally with a 95% confident interval. Both methods are agreed with experimental result.

MODELS FOR TOOL LIFE

The proposed linear model relationship between the machining responses and machining independent variables can be represented by the following:

$$y = mCuttingspeed + nFeedrate + pAxialdepth + qRadialdepth + C \tag{1}$$

Where y is the response, C, m, n, p and q are the constants. Equation (1) can be written in the following form:

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 \tag{2}$$

Where y is the response, x_0 = 1(dummy variables), x_1 = cutting speed, x_2 = Feed rate, x_3 = Axial depth and x_4 = Radial depth. β_0 = C and β_1, β_2, β_3, and β_4 are the model parameters. In most cases, the response surface variables demonstrate some curvature in most ranges of the cutting parameters. Therefore, it would be useful to consider also the second order model in this study. The second order model helps understand the second order effect of each factor separately and the two-way interaction amongst these factors combined. This model can be represented by the following equation:

$$y'' = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{11} x_1 x_2 + \beta_{12} x_1 x_3 + \beta_{13} x_1 x_4 + \beta_{14} x_2 x_3 + \beta_{15} x_3 x_4 \tag{3}$$

EXPERIMENTAL PROCEDURE

Experimental design for RSM

The parameters β_0, β_1, β_2, …etc, appearing in Eq. 2, are determined using the method of least squares. The calculations are performed using statistical software. In order to reduce the total number of cutting tests and allow simultaneous variation of the four independent factors, a well-designed experimental procedure has to be followed.

In machining research, the Box-Behnken design has found a broad application compared to other experiment designs used for RSM. The Box-Behnken design is based on the combination of the factorial with incomplete block designs. It does not require a large number of tests as it considers only three levels (-1, 0, 1) of each independent parameter (Box and Behnken, 1966). The levels of the four input independent variables are given in Table 1. The highest and lowest values of the parameters are taken from the preliminary tests. The Box-Behnken design is normally used for non-sequential experimentation, when a test is conducted only once. It allows an efficient evaluation of the parameters in the first and second order models. Using statistical software the cutting conditions of 29 experiments are generated and the experiments are conducted randomly to minimise errors. In order to calculate the experimental error, the 29 experiments consider five times repeating of central point of the cutting conditions. After a series of preliminary trial tests had been conducted and based on the recommendations given by the tool and workpiece manufacturers, the cutting conditions of the main experiments were established (Table 2).

Test work piece, tool material and experimental setup

The current study is concerned with investigating the effect of four factors (cutting speed, feed, axial- and radial depth of cut) on the tool life when end milling of modified AISI P20 tool steel with coated carbide inserts.

Generally, AISI P20 is a chromium-molybdenum alloyed steel which is considered as a high speed steel used to build moulds for plastic injection and zinc die-casting, extrusion dies, blow moulds, forming tools and other structural components. The modified form of AISI P20 is distinguished from normal P20 steel by the balanced sulphur content (0.015%) which gives the steel better machinability and more uniform hardness in all dimensions. Modified AISI P20 possesses a tensile strength of 1044 MPa at room temperature and a hardness ranging from 280 to 320 HB. The work piece used in this study was prehardened and tempered to a minimum hardness of 300 HB and was provided by ASSAB (Sweden). The approximate chemical analysis is shown in Table 3.

The cutting tool used in this study is a 0º lead – positive end milling cutter of 31.75 mm diameter. The end mill can be equipped with two square inserts whose all four edges can be used for cutting. The tool inserts were made by Kennametal and had an ISO catalogue number of SPCB120308 (KC735M). In this study, only one inserts per one experiment was mounted on the cutter. The insert had a square shape, back rake angle of 0º, clearance angle of 11º, and nose radius of 0.794 mm and had chip breaker. KC735M inserts are coated with a single layer of TiN. The coating is accomplished using PVD techniques to a maximum of 0.004 mm thickness.

The 29 experiments were performed in a random manner on Okuma CNC machining centre MX-45 VA and using a standard coolant. Each experiment was stopped after 85 mm cutting length. Each experiment was repeated three times using a new cutting edge every time to obtain very accurate readings of the tool life. A cutting pass was conducted in such a way that a shoulder, of depth ranging from 1 to 2 mm, and width of 2 to 5 mm, was produced. From the microscope, the flank wear was measured as shown in

Table 2. Conditions of cutting experiments according to Box-Behnken design.

Experiment number	Cutting speed, V_c (m/min)	Feed, f (mm/rev)	Axial depth of cut, a_a (mm)	Radial depth of cut, a_r (mm)
1	140	0.15	1	2
2	140	0.2	1	3.5
3	100	0.15	1	3.5
4	180	0.15	1	3.5
5	140	0.1	1	3.5
6	140	0.15	1	5
7	100	0.15	1.5	2
8	140	0.1	1.5	2
9	100	0.2	1.5	3.5
10	140	0.15	1.5	3.5
11	180	0.2	1.5	3.5
12	180	0.15	1.5	2
13	140	0.2	1.5	2
14	140	0.2	1.5	5
15	140	0.15	1.5	3.5
16	180	0.1	1.5	3.5
17	100	0.1	1.5	3.5
18	100	0.15	1.5	5
19	140	0.1	1.5	5
20	180	0.15	1.5	5
21	140	0.15	1.5	3.5
22	140	0.15	2	5
23	140	0.2	2	3.5
24	140	0.1	2	3.5
25	140	0.15	2	2
26	100	0.15	2	3.5
27	180	0.15	2	3.5
28	140	0.15	1.5	3.5
29	140	0.15	1.5	3.5

Figure 1. Firstly draw the horizontal line as the reference line, then draw the vertical line from the reference line to measure the flank wear.

RESULTS AND DISCUSSION

Development of first order tool life model

Tool life can be found with the below formula (Krar, 1995):

$$\frac{TL}{Fm} \qquad (4)$$

Where *Fm* is feed in mm/min and *TL* is total length. The first order linear equation for predicting the tool life is expressed as:

Table 3. Chemical analysis of modified AISI P20, %.

C	0.38
Si	0.30
Mn	1.50
Cr	1.90
Mo	0.15
S	0.015
Fe	Balance

$$y = 47.76 - 0.12x_1 - 141.03x_2 + 4.43x_3 - 1.83x_4 \qquad (5)$$

The equation shows that the tool life decreases with increase of the cutting speed, the feed, radial depth and axial depth. The first order being used to predict the tool life, since it is included all the parameters and the quadr-

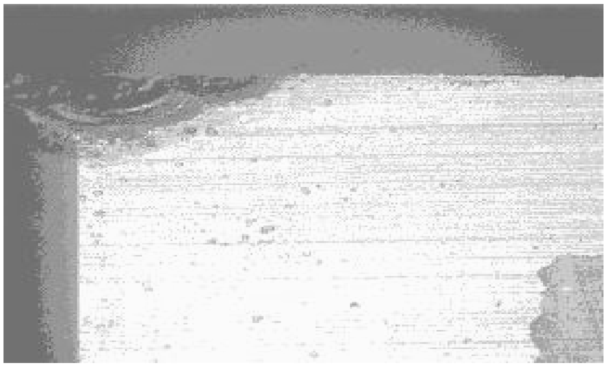

Figure 1. Measurement of flank wear.

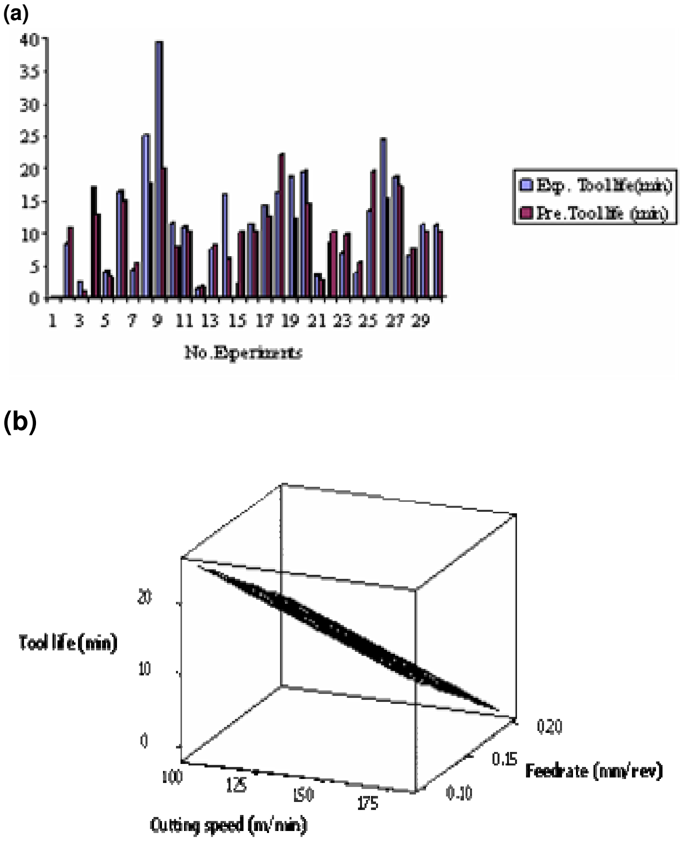

Figure 2. (a) Tool life values obtained by experimentation and the values predicted by the first order model; (b) The tool life contours at medium level (axial depth is 1.5 mm and radial depth 3.5 mm.

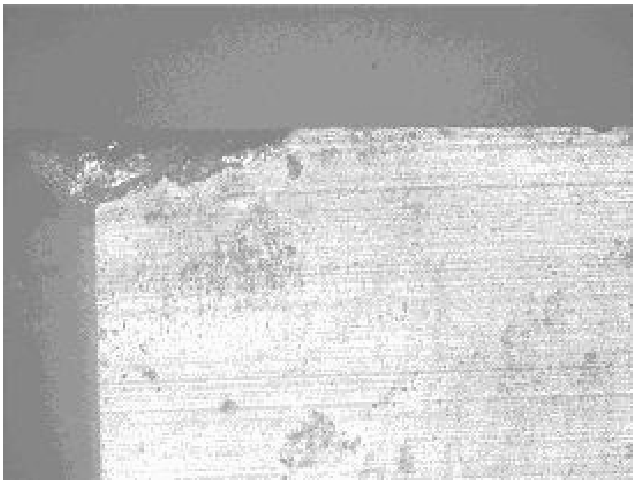

Figure 3a. Microscope picture of cutting tool at the following conditions: cutting speed = 100 mm/min, feedrate = 0.2 mm/rev, axial depth = 1.5 mm radial depth = 3.5 mm and tool life = 11.48 min.

atic equation used to find the interaction of the parameters. Minitab has employed as the statistical software. The feedrate has the most dominant effect on the tool life, followed by the cutting speed, axial depth and radial depth. Hence, a better tool life is obtained with the combination of less cutting speed and low feed. According to Choudhury (1995) the effect of feed on tool life is much more pronounced than the effect of speed. Alauddin et al. (1997) found that an increased in the speed, the feed, and the axial depth of cut decreased the tool life.

Figure 2a shows the tool life values obtained by experimentation and the values predicted by the first order model. It is clear that the predicted values are very close to the experimental readings.

The adequacy of the first order model was verified using the analysis of variance (ANOVA). At a level of confidence of 95%, the model was checked for its adequacy. As it is shown in Table 4, indicates that the model is adequate since the P values of the lack-of-fit are not significant and F- statistics is 3.58. This implies that the model could fit and it is adequate.

The developed linear model Equation 5 was used to plot contours of the tool life at different values of axial and radial depth of cut. Figure 2b shows the tool life contours at medium level (axial depth is 1.5 mm and radial depth 3.5 mm). It is clear that the reduction in cutting speed and feed rate will cause the tool life increase dramatically.

From the Figure 2 a the tool life at the combination low cutting speed and feedrate (100 m/min and 0.15 mm/rev, 140 m/min and 0.1 mm/rev) ranged from 14 to 39 min, but with the combination of high cutting speed and feedrate (180 m/min and 0.2 mm/rev) the tool life was reduced by twice to three times. This is explained as in high cutting speeds, the cutting tool edge experienced larger chip loads that caused more intensive wear. In addition, during high speed cutting, the lubricant effect weakens as it becomes difficult for the lubricant to access the cutting edge due to the increased tool speed. The microscope image of carbide insert after machining P20 tool steel with low speed and high feedrate are shown in Figure 3a-d. The shows the microscope image of carbide inserts after machining P20 tool steel with high speed and high feedrate are shown in Figure 4a-c.

Table 4. Variance analysis for first order tool life model.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	4	919.40	919.40	229.85	3.85	0.016
Linear	4	919.40	919.40	229.85	3.85	0.016
Residual Error	22	1314.19	1314.19	59.74		
Lack-of-Fit	19	1258.66	1258.66	66.25	3.58	0.160
Pure Error	3	55.53	55.53	18.51		
Total	26	2233.59				

Table 5. Variance analysis for second order tool life model.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	1362.75	1362.75	97.34	1.34	0.308
Linear	4	919.40	685.03	171.26	2.36	0.112
Square	4	220.07	264.86	66.21	0.91	0.488
Interaction	6	223.28	223.28	37.21	0.51	0.788
Residual error	12	870.84	870.84	72.57		
Lack-of-fit	9	815.31	815.31	90.59	4.89	0.109
Pure error	3	55.53	55.53	18.51		
Total	26	2233.59				

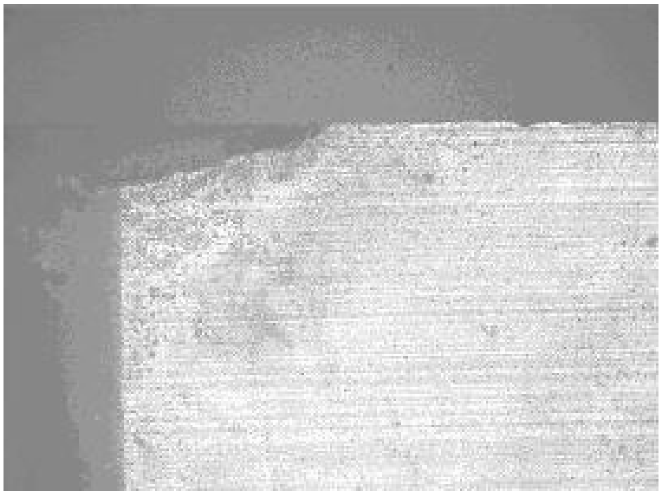

Figure 3b. Microscope picture of cutting tool at the following conditions: cutting speed = 140 mm/min, feedrate = 0.1 mm/rev, axial depth = 1.5 mm radial depth = 2 mm and tool life = 39.46 min.

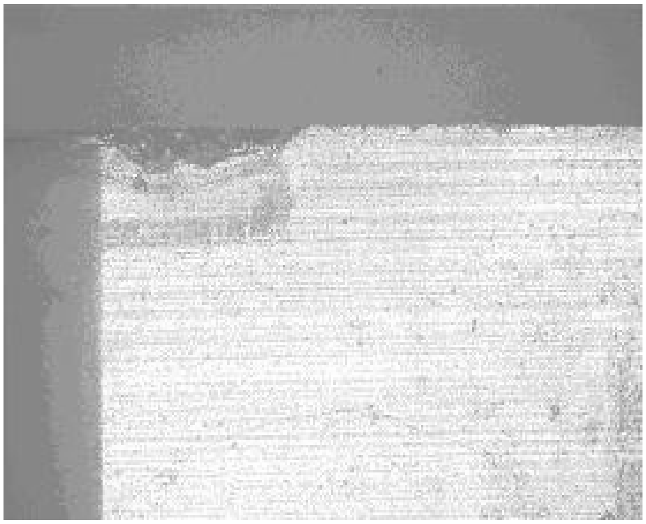

Figure 3c. Microscope picture of cutting tool at the following conditions: cutting speed = 100 mm/min, feedrate = 0.15 mm/rev, axial depth = 1.5 mm radial depth = 2 mm and tool life = 25.10 min.

Development of second-order tool life model

The second-order model was developed to obtain the interaction between the variables. The model equation is:

$$y' = 1.879 + 0.66x_1 - 92.484x_2 + 41.24x_3 - 1.75x_4 - 0.0011x_1^2 + 228.92x_2^2 - 5.40x_3^2 + 1.38x_4^2 - 1.13x_1x_2 - 0.05x_1x_3 - 0.068x_1x_4 - 4.39x_2x_3 + 61.4x_2x_4 - 5.73x_3x_4 \quad (6)$$

Prediction value is shown in Figure 5a. Table 5 shows the 95% confidence interval for the experiments and the analysis of variance. For the second-order model, the P value for lack of fit is 0.109. Therefore, the model is adequate. The variables not significantly interact among them since P value is 0.788 (>0.05). Equation 6 is used to develop the surface plot as shown in Figure 5b.

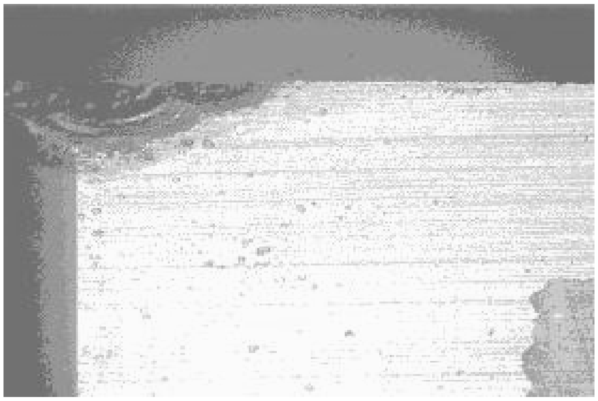

Figure 3d. Microscope picture of cutting tool at the following conditions: cutting speed = 100 mm/min, feedrate = 0.15 mm/rev, axial depth = 1.5 mm radial depth = 5 mm and tool life = 18.70 min.

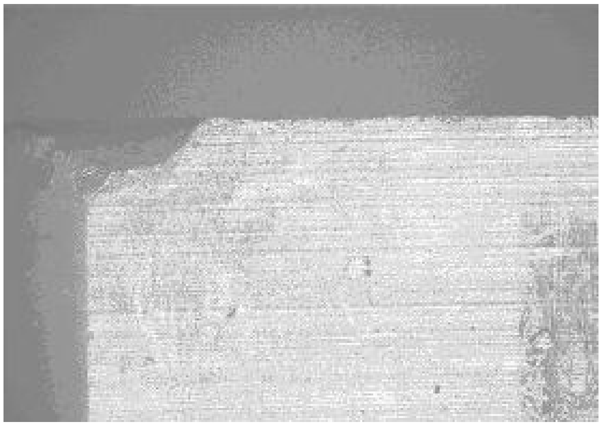

Figure 4a. Microscope picture of cutting tool at the following conditions: cutting speed = 180 mm/min, feedrate = 0.15 mm/rev, axial depth = 1 mm radial depth = 3.5 mm and tool life = 3.94 min.

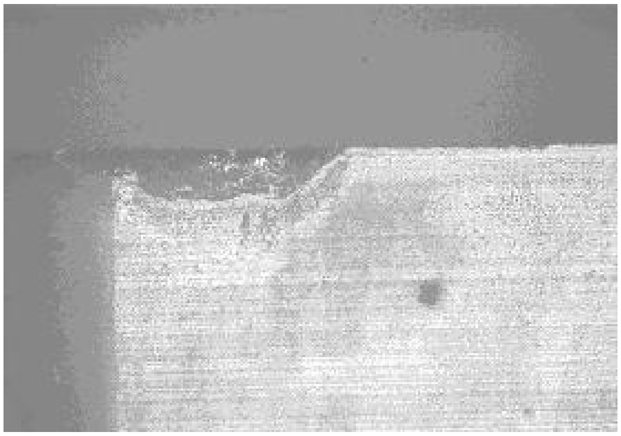

Figure 4b. Microscope picture of cutting tool at the following conditions: cutting speed = 180 mm/min, feedrate = 0.2 mm/rev, axial depth = 1.5 mm radial depth = 3.5 mm and tool life = 1.30 min.

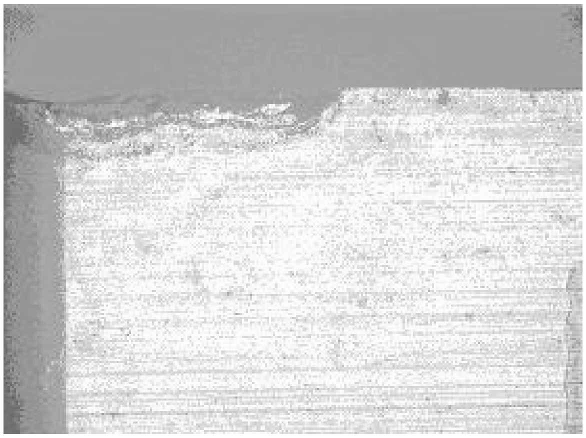

Figure 4c. Microscope picture of cutting tool at the following conditions: cutting speed = 180 mm/min, feedrate = 0.15 mm/rev, axial depth = 1.5 mm radial depth = 5 mm and tool life = 3.46 min.

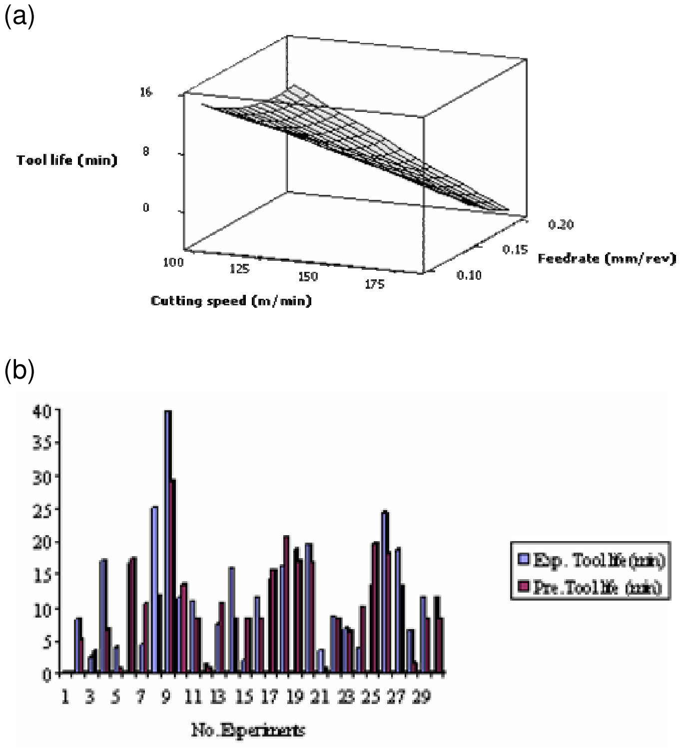

Figure 5. (a) Tool life values obtained by experimentation and the values predicted by the first order model; (b) The tool life contours at medium level (axial depth is 1.5 mm and radial depth 3.5 mm).

Conclusion

A first and second order Mathematic Model were developed to predict cutting parameters for end-milling of P20 tool steel using coated carbide tool steel. The model developed was used to calculate the tool life based on Response Surface Method (RSM). The results were compared by experimentation.

In general, the results obtained from the mathematical models are in good agreement with that obtained from the experiment data's. It was found that the feedrate, cutting speed, axial depth and radial depth played a major role in determining the tool life. On the other hand, the tool life increases with a reduction in cutting speed and feedrate. In addition, the second order model proves the existence of a very strong interaction of the feed rate with axial depth of cut.

For end-milling of P20 tool steel, the optimum conditions that is required to maximize the coated carbide tool life are as follow: cutting speed of 140 m/s, federate of 0.1 mm/rev, axial depth of 1.5 mm and radial depth of 2 mm. Using these parameters, a tool life of 39.46 min was obtained.

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REFERENCES

Alauddin MA, Baradie EL, Hashmi MSJ (1997). "Prediction of tool life in end milling by response surface methodology", 71: 456-465.

Box GEP, Behnken DW (1960). Some new three levels designs for the study of quantitative variables, Technometrics. 2: 455-476.

Hicks CR (1993). fundamental Concepts in the Design of Experiments, fourth ed., Saunders College Publishing, Holt, Rinehart, and Winston.

Hill WJ, Hunter WG (1966). A review of response surface methodology: a literature survey, Technometrics 8: 571-590.

Mead R, Pike DJ (1975). A review of response surface methodology from a biometric viewpoint, Biometrics 31: 803-851.

Metal cutting theory and practice by David a. Stephenson and John S.Agapiou, publish by Marcel Dekker, Inc, (1997). Technology of Machine Tools,Fourth Edition; by Krar Ostwald ;publish by McGraw – Hill;(1995).