MULTIFACTORIAL MATHEMATICAL MODELS OF TOOL LIFE FOR TURNING OPERATION BASED ON TOOL WEAR AND CUTTING PARAMETERS

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ABSTRACT

One of the most significant factors in metal cutting is tool life. The presented research displays a first order predictive multifactorial mathematical model for defining the effect of tool wear and cutting parameters on tool life during turning 42CrMo4 steel with PVD TiAlN/TiN multi-layer coated tungsten carbide inserts, under dry cutting, using the central composite design of experiments method (DoE) with four factors at three levels. Tool life is defined as the of cutting time that tool can be used. Tool wear describes the gradual loss of cutting tool due to regular operation. Response surface methodology (RSM) has been applied for developing model forms of multiple regression equations correlating dependent parameters and tool life with cutting speed, feed rate, depth of cut and tool wear.

Keywords: Multifactorial, Predictive, Parameters, Turning, Linear, Regression, Tool life, Wear, Model

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1. INTRODUCTION

During the course of history people have changed the manufacturing process dramatically. Instead of items being produced by hand, the owners of the facilities created ways to have machines to produce the items. Metal cutting process is widely used in engineering industries. For a machining process such as turning, cutting conditions like cutting speed, feed, depth of cut plays salient role in the efficient use of a machine tool and thus improving its tool life [1].

The selection of proper cutting tool is an important parameter in the machining process of a part in production. It performs the cutting action that helps in getting required surface finish
and accuracy of the part. In order to perform these tasks the tool should possess some special characteristics. Some of the important characteristics are hardness, toughness, wear resistance and chemical stability or inertness with respect to the workpiece material [2]. It helps to withstand wear resistance and serve for long period of time to produce more number of components with same accuracy. Machining is an important part of metal manufacturing process to achieve desired shape, good dimensional accuracy and aesthetic requirements. In modern machining process while using the CNC machine tools the cutting tool with various types of tool inserts will play a vital role in machining process and in improving the surface finish. Many cutting tool manufacturing organizations globally with their rich experience of research and development, invented different ways of enhancing the life of cutting tool in order to optimize the rate of the production and to reduce the cost of production, which is the objective of the manufacturing Industry. [3].

The tool wear of cutting tool has a very strong impact on product quality as well as on the efficiency of machining processes overall despite the current high automation level in the machining industry, a few key issues prevent complete automation of the entire turning process. One of these issues is tool wear, which is usually measured of the machine tool and is still done by hand under a toolmaker’s microscope. There is no any industry wide procedure for automating the process of measuring wear, furthermore, such conventional wear measurement requires stopping the automated turning, removing the tool, measuring the tool and putting the tool back to the holder, which is a considerable time loss relative to the tool’s life, therefore the in-line characterization of cutting tool wear is crucial for cutting cycle times and costs, as well increasing the overall efficiency of the machining process [4].

The primary objective of this research is to develop a predictive mathematical relationship of the tool life model (min) for Cr42Mo4 steel with PVD TiAlN/TiN multi-layer coated carbide inserts under dry machining conditions, as a function of the cutting parameters such as cutting speed (m/min), feed rate (mm/rev), depth of cut (mm) and tool wear (mm).

2. TOOL WEAR AND TOOL LIFE

The life of a cutting tool can be terminated by a number of means, although they fall broadly into two main categories: a) gradual wearing of certain regions of the face and flank of the cutting tool, and b) abrupt tool failure. Considering the more desirable case a) the life of a cutting tool is therefore determined by the amount of wear that has occurred on the tool profile and which reduces the efficiency of cutting to an unacceptable level, or eventually causes tool failure (case b). When the tool wear reaches an initially accepted amount, there are two options, 1) to resharpen the tool on a tool grinder, or 2 to replace the tool with a new one. This second possibility applies in two cases, (i) when the resource for tool resharpening is exhausted, or (ii) the tool does not allow for sharpening, e.g. in case of the indexable carbide inserts [5].

Definition of tool life: Tool life generally indicates, the amount of satisfactory performance or service rendered by a fresh tool or a cutting point till it is declared failed. Tool life is defined in two ways [9]: a) In R&D laboratories, actual machining time (Tc) by which a fresh cutting tool (or point) satisfactorily works after which it need replacement or reconditioning. The modern tool hardly fail prematurely or abruptly by mechanical breakage or rapid plastic deformation. Those fail mostly by wearing process which systematically grows slowly with machining time. In the case, tool life means the span of actual machining time by which a fresh tool can work before attaining the specified limit of tool wear. Mostly tool life id decided by the machining time till flank wear, V_B reaches 0.3 mm or crater wear, K_T reaches 0.15 mm. (b) In industries or shop floor: The length of time (TL) of satisfactory
Tool wear is a time dependent process. As cutting proceeds, the amount of tool wear increases gradually. But tool wear must not be allowed to go beyond a certain limit in order to avoid tool failure. The most important wear type from the process point of view is the flank wear, therefore the parameter which has to be controlled is the width of flank wear land, $V_B$ Figure 1. This parameter must not exceed an initially set safe limit, which is about 0.4 mm for carbide cutting tools. The safe limit is referred to as allowable wear land (wear criterion), $V_{Bk}$. The cutting time required for the cutting tool to develop a flank wear land of width $V_{Bk}$ is called tool life, $TL$, a fundamental parameter in machining.

**2.1. Tool Life Evaluation Methodology**

**2.1.1. Taylor’s tool life equation**

Wear and hence tool life of any tool for any work material is governed mainly by the level of the machining parameters i.e., cutting velocity, ($v_C$), feed, ($f$) and depth of cut ($a$). Cutting velocity affects maximum and depth of cut minimum. The usual pattern of growth of cutting tool wear (mainly $V_B$), principle of assessing tool life and its dependence on cutting velocity are schematically shown in Figure 2.

The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered as indicated in Figure. 2.

If the tool lives, $T_1$, $T_2$, $T_3$, $T_4$ etc. are plotted against the corresponding cutting velocities, $V_1$, $V_2$, $V_3$, $V_4$ etc. as shown in Figure. 3, a smooth curve like a rectangular hyperbola is found to appear. When F. W. Taylor (1907) plotted the same figure taking both $V$ and $T$ in log-scale, a more distinct linear relationship appeared as schematically shown in Figure. 4. With the slope, $n$ and intercept, $c$, Taylor derived the simple equation as:

$$V \cdot T^n = C$$

**Figure 1** Flank wear observed in cutting tools [8]

**Figure 2** Growth of flank wear and assessment of tool life [9]
Where; V- cutting speed, T- tool life, n, C- Taylor constants (empirical). The values of both ‘n’ and ‘C’ depend mainly upon the tool-work materials and the cutting environment (cutting fluid application).

2.1.2. Modified Taylor’s Tool Life equation

In Taylor’s tool life equation, only the effect of variation of cutting velocity, V_C on tool life has been considered. But practically, the variation in feed rate(f) and depth of cut (a) also play role on tool life to some extent. Taking into account the effects of all those parameters, the Taylor’s tool life equation has been modified as:

\[
TL = \frac{C_T}{V_c^{x_1} \cdot f^{y_1} \cdot a^{z_1} \cdot \alpha^{w_1}}. \tag{2}
\]

Where,

TL = tool life in min

C_T – a constant depending mainly upon the tool – work materials and the limiting value of V_B undertaken.

x_1, y_1 and z_1 – exponents so called tool life exponents depending upon the tool – work materials and the machining environment.

Generally, x_1 > y_1 > z_1 as V_C affects tool life maximum and t minimum. The values of the constants, C_T, x_1, y_1 and z_1 are available in Machining Data Handbooks or can be evaluated by machining tests.

The value of C depends also on the limiting value of V_BB undertaken. This basic relationship was later extended to the more general form:

\[
TL = \frac{C_T}{V_c^{x_1} \cdot f^{y_1} \cdot a^{z_1} \cdot V_B^{w_1}}. \tag{3}
\]

Many authors suggested linear and exponential empirical models for tool life as functions of machining parameters [3, 10], by the following: Four parameters were selected for this study: cutting speed (V_c), feed rate (f), depth of cut (a) and tool wear (V_B), therefore the Eq.(2) will appear as in the following:

\[
TL=C_T \cdot V_c^x \cdot f^y \cdot a^z \cdot V_B^w \tag{4}
\]

where, TL is the tool life in (min), V_c - cutting speed in m/min, f - feed rate in (mm/rev), a - depth of cut in (mm) and V_B-flank wear land in (mm), respectively x, y, z and ware constants.

Figure 3 Cutting velocity – tool life relationship Figure 4 Cutting velocity vs tool life on a log-log scale
3. METHODS AND PROCEDURE

3.1. Design of experiment

The parameters (factors) considered in this paper are cutting speed \( v_c \), feed rate \( f \), depth of cut \( a \) and flank tool wear. The cutting tool life was chosen as a target function (response, output).

Since it is obvious that the effects of factors on the selected target function are nonlinear, an experiment with factors at three levels was set up (Table 1).

A design matrix was constructed on the basis of the selected factors and factor levels (Table 2). The selected design matrix was a full factorial design \( N=2^k+n_0 \) \((k= 4 \text{- number of factors, } n_0 = 8 \text{- number of additional tests for four factors})\) consisting of 24 rows of coded/natural factors, corresponding to the number of trials. This design provides a uniform distribution of experimental points within the selected experimental hyper-space and the experiment with high resolution.

3.2. Choice of Process Parameters

The working ranges of the parameters for subsequent design of experiment have been selected in accordance with the normal working ranges for such operation. In the present experimental study; spindle speed, feed rate, depth of cut and flank tool wear have been considered as process variables the most important process parameters affecting the tool tool life.

In order to develop the tool life prediction model, four factors and three levels for each of them are selected. The selected process parameters for the experiment with their limits, units and notations are given in table 1.

Machining conditions used in the experiment are shown in Table 1. All of the trials have been conducted on the same machine tool, with the same tool type and the same cutting conditions.

3.3. Experimental setup

**Machine tool**: Production lathe PA22, \( P = 12 \text{ kW} \), speed range \( n = 22 - 2200 \text{ rpm} \), feed rate range \( f = 0.08 - 2.5 \text{ mm/rev} \), Max. workpiece diameter \( d_{\text{max}} = 450 \text{ mm} \), Distance from chuck to the tail stock \( L = 2250 \text{ mm} \).

**Workpiece material**: Hardened 42CrMo4 (EN 10250) steel at 45 HRC, with dimensions \( L \times D =300 \times 80 \text{ mm} \). Heat treated at temperature 800-8500 \( ^\circ \text{C} \), cooled in the furnace to the temperature 460 \( ^\circ \text{C} \) and complete annealing the steel in the air. Its chemical composition is as follows:\((0.39-0.42)\% \text{ C}; (1.04-1.06\%) \text{ Cr}; (0.22-0.24\%) \text{ Mo}; (0.72-0.76\%) \text{ Mn}; 0.2-0.22\% \text{ Si}\) other components approx., 98 % Fe. Tensile: strength: 900-1000 \( \text{N/mm}^2 \), Brinell hardness: 260-330 \( \text{N/mm}^2 \).

**Cutting inserts**: Experiments were performed using commercially available PVD TiAlN/TiN multi-layer coated carbide inserts type SNMM120404, tool holder ISO PCBNR /L 2020K12.

**Measuring equipments**: Microscope Carl Zeiss 15x8, Spectrometer Metorex Arc-met 930 , Hardness meter Krautkramer-mic.10.DL.
3.4. Tool Life Measurement

Tool life (TL) was measured by the number of cuts taken by the insert to reach a set wear criterion $V_B$ or when the maximum width of the end clearance wear ($V_{C_{max}}$) or nose wear ($N_{V_{max}}$) reached $\approx 0.4$ mm or the occurrence of the catastrophic failure. The tool life criteria is determined using ISO 3685-1977(E) catastrophic failure [11].

3.4.1. Flank Wear Measurement

Flank wear on the cutting insert was measured every 2 minutes on the work piece 42CrMo4 sets a recommended uniform wear criterion of $WB \approx 0.2$ mm (low level), respectively $V_B \approx 0.28$ mm (middle level) and $V_B \approx 0.4$ mm (high level). After recording the flank wear, the insert was fastened back the tool holder.

Table 1 Experimental setup at three level factor

<table>
<thead>
<tr>
<th>No.</th>
<th>Factors</th>
<th>Code level</th>
<th>Low level (At the same time, the hosen for a target function (response, output)&gt;ess.e number of studies have investigated the ge)</th>
<th>Middl e level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$v_c$, m/min</td>
<td>$X_1$</td>
<td>80</td>
<td>125</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>f, mm/rev</td>
<td>$X_2$</td>
<td>0.142</td>
<td>0.196</td>
<td>0.249</td>
</tr>
<tr>
<td>3</td>
<td>a, mm</td>
<td>$X_3$</td>
<td>0.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>$V_B$, mm</td>
<td>$X_4$</td>
<td>0.2</td>
<td>0.28</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Entire experiment was carried out in the dry condition, during the turning process, and results are shown in Table 2.

Table 2 Experimental results of tool life

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Coded factors</th>
<th>Tool life (TL) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_0$</td>
<td>$X_1$</td>
<td>$X_2$</td>
</tr>
<tr>
<td>1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>+1</td>
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</tr>
<tr>
<td>3</td>
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<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>-1</td>
</tr>
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<td>7</td>
<td>+1</td>
<td>-1</td>
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<td>1</td>
</tr>
<tr>
<td>11</td>
<td>+1</td>
<td>1</td>
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</table>
Multifactorial Mathematical Models of Tool Life for Turning Operation Based On Tool Wear and Cutting Parameters

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<td>12</td>
<td>+1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>120.4</td>
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<td>1</td>
<td>-1</td>
<td>-1</td>
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<td>1</td>
<td>-1</td>
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<td>1</td>
<td>-1</td>
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</tr>
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<td>1</td>
<td>1</td>
<td>1</td>
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<td>0</td>
<td>0</td>
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<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>19</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>20</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>45.40</td>
</tr>
<tr>
<td>21</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>88.60</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>23</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>66.30</td>
</tr>
<tr>
<td>24</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>50.40</td>
</tr>
</tbody>
</table>

4. REGRESSION BASED MODELING
The main task for regression analysis is to show relationship between tool life and machining independent variables.

Multiple linear regression models for tool life can be obtained by applying a logarithmic transformation that converts non-linear form of Eq. (4) into following linear mathematical form:

\[
\ln TL = \ln C_T + x \ln V_a + y \ln f + z \ln a + w \ln V_B
\]  

(5)

The linear model of Eq. (5) in term of the estimated response can be written as:

\[
\hat{Y} - \varepsilon = p_0 x_0 + p_1 x_1 + p_2 x_2 + p_3 x_3 + p_4 x_4
\]  

(6)

Where; \(y\) is the logarithmic value of the tool life, \(p_0, p_1, p_2, p_3\), are regression coefficients to be estimated, \(x_0\) is the unit vector, \(x_1, x_2, x_3, x_4\), are the logarithmic Values of cutting speed, feed rate, depth of cut, workpiece hardness and \(\varepsilon\) is the Random error.

The above equation in matrix form becomes:

\[
p = (X'X)^{-1} X' y
\]  

(8)

The fitted regression model is:

\[
\hat{Y} = X
\]  

(9)

The difference between the experimentally measured and the fitted values of response is:

\[
\varepsilon = y - \hat{y}
\]  

(10)

The regression analysis technique using least squares estimation was applied to compute the coefficients of the exponential model. The following exponential model for tool life was determined and is given, respectively

\[
TL = 532.976 \cdot v_e^{-0.402} \cdot f^{-0.914} \cdot a^{-0.153} \cdot V_B^{1.490}
\]  

(11)
4.1 Adequacy of the model

The predictive mathematical model obtained (11) is adequate as it meet the condition[13]:

\[
F_{R,LF} = \frac{S_{LF}^2}{S_E^2} = \frac{0.38153411 \cdot 8}{0.1094236} = 3.487 \leq F_i = 3.57
\]  

(12)

Where:

\[
S_E = \sum_{u=1}^{n_u} \bar{y}_{0u}^2 - \frac{1}{n_0} \left( \sum_{u=1}^{n_u} \bar{y}_{0u} \right)^2 = 0.7659653 , \text{ respectively};
\]  

(13)

\[
S_E^2 = \frac{S_E}{f_E} = \frac{0.7659653}{7} = 0.1094236
\]  

(14)

\[
S_{LF} = S_R - S_E = 4.57840941, \text{ respectively};
\]  

(15)

\[
S_{LF}^2 = \frac{S_{LF}}{f_{LF}} = \frac{4.57840941}{12} = 0.381534118
\]  

(16)

\[
S_R = \sum_{u=1}^{N} \bar{y}_{eu}^2 - N \sum_{i=0}^{k} \hat{b}_i^2 = 5.344375
\]  

(17)

\[
f_{LF} = f_R - f_E = N - k - 1 - (n_0 - 1) = 12
\]  

(18)

4. RESULTS AND DISCUSSION

Table 2 presents experimental results of tool life criteria TL for various combinations of cutting speed, feed rate, depth of cut and tool wear to full factorial design. Minimal value of tool life was obtained at \( v_c = 200 \text{ m/min} \), \( f = 0.249 \text{ mm/rev} \), \( a = 2 \text{ mm} \) and \( V_B = 0.2 \text{ mm} \) (test No.15). That means increasing of cutting speed, feed rate, depth of cut lead to decreasing of tool life, while increase with tool wear.

Maximal value of tool life TL was registered at \( v_c = 80 \text{ m/min}, f = 0.142 \text{ mm/rev}, a = 0.5 \text{ mm} \) and \( V_B = 0.4 \text{ mm} \), (test No. 2).

It is found that tool wear has the most significant effect \((1.5)\) on tool life, followed by feed rate\((0.933)\), cutting speed \((0.415)\) and depth of cut \((0.159)\).

Figure 3 appears the dependence of tool life on: a) tool wear and various values of feed rate, for \( a = 1.0 \text{ mm} \) and \( v_c = 125 \text{ m/min} \), b) depth of cut and various values of feed rate, for \( V_B = 0.28 \text{ mm} \) and \( v_c = 125 \text{ m/min} \) c) cutting speed and various values of tool wear, for \( f = 0.196 \text{ mm/rev}, a = 1 \text{ mm} \) and d) feed rate and various values of tool wear, for, \( a = 1 \text{ mm} \) and \( v_c = 125 \text{ m/min} \).

Figure 3 (a,b,c and d) highlights the main factor plots for TL appears to be an almost linear decreasing function of \( v_c, f, a, \) and increasing of \( V_B \).
4. CONCLUSIONS
The developed predictive model of the tool life can be successfully applied on other operations and by using the experimentally analytical procedure of determining the optimal values of machinability parameters to increase the process efficiencies and part quality. From the above results and discussion it is concluded that tool life will decrease with increasing of cutting speed, feed rate and depth of cut, while increase with tool wear. The exponent of tool durability (n) in Taylor-s equation can be selected according to the criteria of minimizing the impact of tool wear on the cutting speed. By choosing the adequate parameters of the cutting process and tool life (T) can be controlled the tool wear process, so that any operation can be realized in the required time.

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