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Estimating tool life from measurements during longitudinal turning process using linear least squares

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A B S T R A C T

This research paper presents a procedure to estimate parameters for the modified Taylor equation using experimental measurement. The end-of-life times for each laboratory test were recorded well. The tool life has been measured by observing an abnormal change in the observed pitch of a sound from the cutting tool. The objective of this research is to understand the wear mechanisms of the insert carbide tool for different speed machining under dry condition using longitudinal turning process. The tool life equation obtained by linearizing the expanded Taylor tool life equation and solving a linear system of equations using linear least squares. In this study, both the experimental data and analytical solution show reasonable fit. The estimated tool life model simulates the measured end of tool life using the sound inspection method. An additional analysis to confirm effects of each cutting parameter on the tool life have been presented. Estimating the Tool life (T_L) model using nonlinear least squares could give more accurate results which is going to be considered in the future study. The significance of this study is to save resources in the manufacturing industry by avoiding estimating tool life during turning process. Since that cause delay in the production time and waste of resources.

تقدير عمر الأداة من القياسات أثناء عملية الخراطة الطولية باستخدام المربعات الصغرى الخطية

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الكلمات المفتاحية:
الخراطة الطولية.
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المربعات الصغرى الخطية.
تقدير تلف الأداة.

الملخص

هذه الورقة البحثية تقدم طريقة لتقدير معلمات معادلة تايلور المعدلة باستخدام القياس التجريبي. تم تسجيل أوقات نهاية العمر لكل اختبار معملي بشكل جيد. تم قياس عمر الأداة من خلال ملاحظة تغير غير طبيعي في طبقة الصوت المرصودة من أداة القطع. الهدف من هذا البحث هو فهم آليات التلف لأداة قطع نوع كربيد (Insert Carbide) عند سرعات مختلفة تحت ظروف تشغيل جافة باستخدام عملية الخراطة الطولية.. تم الحصول على معادلة عمر الأداة عن طريق التحوير الخطي لمعادلة عمر الأداة الغير خطية لتايلور الموسعة ومن ثم حل نظام المعادلات الخطية باستخدام المربعات الصغرى الخطية. في هذه الدراسة، تظهر كل من البيانات التجريبية والحل التحليلي ملاءمة معقولة. يحاكي نموذج عمر الأداة المقدر نهاية عمر الأداة المقاسة باستخدام طريقة الفحص الصوتي. تم تقديم تحليل إضافي لتوضيح تأثيرات كل معاملات القطع علي العمر لأداة القطع. إن تقدير نموذج عمر الأداة (T_L) باستخدام المربعات الصغرى غير الخطية يمكن أن يعطي نتائج أكثر دقة والتي سيتم أخذها في الاعتبار في الدراسة المستقبلية. تكمن أهمية هذه الدراسة في توفير الموارد في الصناعة التحويلية من خلال تجنب تقدير عمر الأداة أثناء عملية الخراطة. لأن ذلك يسبب تأخير في وقت الإنتاج وإهدار للموارد.

1. Introduction

Modelling and Optimizing the Tool life is essential to obtain higher productivity. Therefore, the cutting parameters must be chosen carefully. The optimal cutting parameters will reduce costs and increase productivity (MRR) and quality. These studies searched for the optimal machine operation parameters to control the tool wear. Effect of the cutting parameters on the tool life are usually modelled using Taylor equation which gives the tool life (end of life in minutes) as a function of the cutting speed, depth of cut and feed rate. These cutting parameters

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influence the cutting force, cutting temperature, specific energy, etc. Therefore, an intensive investigation of the tool life in response to the implemented cutting parameters is a crucial step toward maintaining long machine production and reducing tool regrinding and replacement cost.

In this study, the used workpiece material to evaluate the tool life of a carbide insert cutting tool, was the C45 mild carbide steel (0.45% carbon). The C45 mild carbide steel has been extensively used to make parts such as: axles, gears, shafts, piston pins, etc. The cutting tool performance must be carefully studied to meet the required initial design specifications with satisfactory finish at lowest cost. To achieve this objective, it is necessarily to model and simulate the cutting process to perform an intensive tool investigation at all possible harm conditions (dry cutting, critical cutting parameters, etc.). Some selected studies will be summarized in this short literature review and aimed as an introductory to some attempt to search for an optimal cutting parameter to maximize the tool life. Al-Ahmari et al. [1] developed empirical models to predict three machining functions (tool life, cutting force and surface roughness), using cutting tool measurements for turning austenitic AISI 302. They approximated the relationships between estimated machining functions and cutting parameters using multiple linear regression analysis techniques (RA), response surface methodology (RSM), and computational neural networks (CNN). They concluded that the results from CNN models are better than that from RA and RSM models. Also, RSM models estimate tool life and cutting force models better than RA models. Bazaz et al. [2] employed dimensional analysis to formulate the tool life model during turning process of metal cutting for small-lot production by considering the effects of cutting speed, feed rate, depth of cut, workpiece hardness, tool hardness, cutting force, and cutting temperature. They concluded that the cutting speed, workpiece material hardness, and feed rate are the most influential factors that influence the estimated tool life. They found that the tool life increases when increasing the tool hardness, and reduces when workpieces hardness was higher. Prince et al. [3] conducted wet-turning experiment to estimate the tool life of coated carbide insert in a CNC lathe machine to cut stainless steel SS316L.

The tool life was estimated using industrial and theoretical method (Taylor's tool life Equation). Theoretical method can be successfully implemented to estimate the tool life to save operator time and machining cost. They found that the Flank wear and brittle wear are the most common cause of tool failure. Kumar et al. [4] studied the tool life and its failure mechanism. They concluded that the geometry of a cutting tool, cutting parameters, and the machining condition (dry or wet) influence tool life, meanwhile, the optimum values of rake and clearance angles are -50 to +100 and 50 to +80 respectively. They also concluded that tool failure increased under the influence of high thermal stresses, wear and mechanical forces. An investigation to measure and analyze the cutting forces and the surface finish performed by Rao et al. [5] using a tungsten carbide tool to cut Aluminum. They varied the depth of cut, speed and feed rate at different conditions, then calculated the tool life, surface finish, cutting force. Their results showed noticeable decreases in the tool life as the cutting force, material removal rate (MRR) and cutting speed increased. Another experimental and analytical studies made by Nexhat and Azem [6] to model a dryly turning of hardened 42CrMo4 steal using a titanium nitride coated tungsten carbide tool when level of hardness changed. They estimate the tool life using experiments and a parameter estimation. They found that tool life decreases when increasing cutting speed, feed rate, depth of cut and material hardness. They also found that the cutting speed has maximum effect of -0.825 and that the depth of cut has minimum effect of -0.248 at all levels of hardness, and the recommended to use the right tool for the right cutting condition in order to increase tool life and productivity. An experiment study to perform a correlation between roughness and the tool flank wear was performed by Equeter et al. [7] using a cutting insert in dry longitudinal turning of AISI 1045, they concluded that the maximal height of the roughness profile related to the most noticeable rise of the cutting tool wear. Eugene at el. [8] studied the wear of carbide P25 inserts tool when turning dryly a medium carbide steel for cutting speed range between 250 m/min and 450 m/min with the emulsion mist, they concluded that machining of steels in emulsion mist environment will be associated with less cutting tools wear rate compared to the pure dry cutting environment. The cutting force, specific energy and cutting temperature have been effectively investigated in many literatures to show how they affect the tool life. One of these studies were performed by Stachurski et al. [9] to develop a mathematical model to calculate the cutting force during wet/dry straight turning of C45. The mathematical model reduces the time–consuming experiments and explains that the cutting forces effected by the cutting speed, and the corner radius, the feed rate. Another study by Stachurski at el. [10] were conducted using longitudinal turning of Ti-6Al-4V ELI alloy (Grade23) to measure the influence of speed of cut and feed rate on changes in the total cutting force and its components. They concluded that the cutting speed has a negligible influence, while feed rate significantly influences the forces applied to the tool. Another investigation was made by Muamar at el. [11] when they machined low carbon steel workpieces under dry and wet turning conditions, using carbide cutting tool with a constant tool nose radius. they studied the influence of the spindle speed, feed rate and depth of cut, on the surface roughness. Their results showed that surface roughness decreases at higher cutting speeds, and it increases as the feed rate increases. Depth of cut showed the minimum effect on the surface roughness. Chou and Song [12] have documented the effect of tool tip radius on turning AISI-52100 steels and evaluated output quality characteristic, tool life, forces applied on the cutting tool and the formation of white layer. They concluded that large tool tip radius produces a good output quality characteristic, but associated with tool wear and a slight increase in the consumed power (specific energy). Another important parameter for study and control the machining process is the cutting temperature which is due to the friction between the tool and the workpiece. A plenty of studies covered this important design parameter. One of these studies was performed by Abhang el at. [13] using turning of EN 31 steel alloy with tungsten-carbide tools to estimate average chip-tool interface temperatures using thermocouples. They concluded that using both optimal cutting parameters and optimal tool tip radius produce an optimal cutting temperature during the process of turning a steel and that an increase in the tool tip radius reduces the cutting temperature. This study represents the procedure to estimation the tool life exponents of the expended Taylor equation for the longitudinal turning experiment by linearizing the nonlinear terms then solving linear system of equations using linear least squares methods. The analytical tool life results were compared to the measured tool life. An extra investigation made on the accuracy in collecting measured tool life sample at the three controlled cutting parameters to show effect of the three cutting parameters on the tool's end of life (tool life). The used workpiece material to evaluate the tool life of a carbide insert cutting tool, was the C45 mild carbide steel (0.45% carbon).

2. Materials and Experimental methods

The material used for conducting experiments is C45 mild carbide steel. The experiment was carried out on lathe machine on the cylindrical workpiece mild steel (57 mm diameter and 500 mm length) with carbide tool and tool life is measured by observing an abnormal change in the pitch of sound from the cutting tool. The experiments were conducted according to the Taguchi design of experiment as per Table-1. The results of 27 tests are shown in Table-2. The experimental work was carried out under a dry cutting environment by using universal turning type sinus 330/3000. Figure 1 shows the cutting machine (SN-126130). The tool life criteria which have been used in this study to detect end of tool life was based on changes in the sound emitting from the operation. Each machining experiment was conducted by using a new cutting tool edge.

Fig. 1: The cutting machine (SN-126130)

A 3^3 factorial design was used to study influence of the cutting parameters on the tool's end of life (tool life). Figure 2 and Table 1, shows these steps. This procedure was applied and repeated for the 27 experiments.

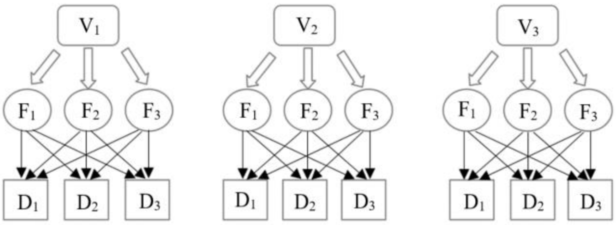


Fig. 2: Flowchart of the 27th excremental procedure

Table 1: The procedure of the experiments.

Cutting parameters	Level-1	Level-2	Level-3
Speed of cut (V) m/min	92.68	122.83	155.63
Feed rate (F) mm/rev	0.09	0.18	0.36
Cutting Depth (D) mm	0.3	0.5	0.8

The insert carbide tool shown in Figure 3 has been used to cut the medium carbide steel "C-45"

(a). Insert Carbide tool (b). Medium carbide steel

Fig. 3: The insert carbide tool & the work material

Experiments have been conducted at three different cutting speeds by varying the other two cutting parameters for each cutting speed. At each cutting speed, three feed rates were performed and at each of them three depths of cuts have been implemented. That makes 27 tests organized in Table 1 and at each test, the tool's end of life was measured by detecting the changes in the sound emitted from the operation as documented in Table 2, column nr. 5.

Table 2: Experimental details.

Sample Nr. $1 \le i \le 27$	Speed of cut V_i - (m/min)	Feed rate F_i - (mm/rev)	Cutting Depth D_i - (mm)	Life time T_{L_i} - (min)
1			0.3	19.13
2		0.09	0.5	10.58
3			0.8	4.20
4			0.3	14.37
5	92.68	0.18	0.5	8.11
6			0.8	3.40
7			0.3	11.0
8		0.36	0.5	5.54
9			0.8	2.27
10			0.3	11.52
11		0.09	0.5	9.00
12			0.8	2.20
13			0.3	8.19
14	122.83	0.18	0.5	6.33
15			0.8	1.55
16			0.3	7.15
17		0.36	0.5	4.10
18			0.8	1.02
19			0.3	7.20
20		0.09	0.5	5.30
21			0.8	1.17
22			0.3	6.10
23	155.63	0.18	0.5	4.35
24			0.8	1.05
25			0.3	4.53
26		0.36	0.5	2.50
27			0.8	0.41

3. Mathematical Model

Taylor has proposed a relationship between tool life, cutting velocity, (V), feed rate (F) and Cutting depth (D). The first attempt to model the tool life has the following form

$$V T_L^n = C \tag{1}$$

Where, the n parameter is the Taylor exponent and the C parameter is constant. Both n and C values effected by the used cutting tool, the workpiece and cutting environment such as wet/dry cutting, etc.

The more accurate relation which has been widely used is the expanded Taylor tool life [13] which defined as

$$V T_L^n \mathrm{F}^{\mathrm{m}} \mathrm{D}^{\mathrm{k}} = C \tag{2}$$

Where, T_L is the tool's end of life (tool life) in minutes, C is a constant effected by both the used cutting tool and the workpiece. The tool life exponents are n, m, and k influenced by the used tool, workpiece and the environment of the machine.

In this study, the temperature of a cutting tool will be approximated by Nathan Cook equation [14], his analytical solution can be used to approximate the cutting temperature,

$$T = \frac{0.4\,U}{\rho C_p}\left(\frac{V t_o}{\alpha}\right)^{0.333} \tag{3}$$

Where T is the cutting temperature, U is the specific energy, V is the cutting velocity, to is the chip thickness before cut, ρCp is the product of the density and the specific heat capacity of workpiece, α is the diffusivity of the workpiece. By combining Eqns. 2 & 3 yields an approximation of the relationship between tool life and the cutting temperature. Equation 4 can be used to see the effect of the controlled cutting parameters on the cutting tool temperature.

$$T_L = \left[\frac{C \quad D^{1-k}}{0.06\,\alpha\left(\frac{\rho C_p}{0.4\,U} T\right)^3 F^m}\right]^{1/n} \tag{4}$$

4. Tool Life Parameter Estimation by Linear Least Squares

The modified Taylor's equation (eqn. 5), used to evaluate the tool life parameters. The exponents n, m, k and C are to be estimated from the experiments for each combination of cutting parameters.

$$V \; T_L^n \; F^m D^k = C \tag{5}$$

At the first look, one can suggest Linearizing the expanded Taylor equation as

$$ln(V) + \mathbf{n}\, ln(T_L) + \mathbf{m}\, ln(F) + \mathbf{k}\, \ln(D) = \ln(C) \qquad (6)$$

Then by collecting the unknown parameters (n, m, k, and C) in vector x (x_1, x_2, x_3, and x_4)

$$\overbrace{\ln(C)}^{x_1} - \overbrace{\mathbf{n}}^{x_2}\, ln(T_L) - \overbrace{\mathbf{m}}^{x_3}\, ln(F) - \overbrace{\mathbf{k}}^{x_4}\, \ln(D) = \overbrace{ln(V)}^{b} \qquad (7)$$

Building the A matrix and the right-hand side vector B

$$\overbrace{1}^{a_{i1}}\, \overbrace{\ln(C)}^{x_1} - \overbrace{\mathbf{n}}^{x_2}\, \overbrace{ln(T_L)}^{a_{i2}} - \overbrace{\mathbf{m}}^{x_3}\, \overbrace{ln(F)}^{a_{i3}} - \overbrace{\mathbf{k}}^{x_4}\, \overbrace{\ln(D)}^{a_{i4}} = \overbrace{ln(V)}^{b_i} \qquad (8)$$

This is the final form of the system of linear equation to be solved

$$\boldsymbol{a_{i1}\, x_1 - a_{i2}\, x_2 - a_{i3}\, x_3 - a_{i4}\, x_4 = b_i}\,, \quad \mathbf{1 \le i \le 27} \qquad (9)$$

The 27th experimental samples give 27 linear equations to be solved to get C, n, m, and k.

The general form of the linear system of equation can be defined as;

$$b_i = a_{i1}x_1 - \sum_{j=2}^{4} a_{ij}x_j \quad for\ 1 \le i \le 27 \qquad (10)$$

The following Table 3 clarify the unknown and known parameters of eqn. 5 & 10.

Table 3: Parameters for the linear system of equations (B = ln(V))

Known parameters from Table 1 ($1 \le i \le 27$)				
b_i $ln(V_i)$	a_{i1} 1	a_{i2} $-ln(T_{L_i})$	a_{i3} $-ln(F_i)$	a_{i4} $-ln(D_i)$
Unknown parameters				
	x_1 $ln(C)$	x_2 n	x_3 m	x_4 k

Where the 27th cutting speeds are $V_i = V_1, V_2, \ldots V_{27}$ and the 27th feed rates are $F_i = F_1, F_2 \ldots, F_{27}$, also the 27th depth of cut are $D_i = D_1, D_2 \ldots, D_{27}$. To get tool life parameters (C, n, m and k), a linear system of equations (27 linear equations) represented by $A\,x = b$. Where Matrix A, vector b & the vector of the solution x can be defined as in Table 4;

Table 4: Matrix A and b, x vectors for the linear system of equations

Matrix A	Vector b	Vector x
$A = \begin{vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ \vdots & \vdots & \vdots & \vdots \\ a_{N1} & a_{N2} & a_{N3} & a_{N4} \end{vmatrix}$	$b = \begin{vmatrix} b_1 \\ b_2 \\ \cdots \\ \vdots \\ b_N \end{vmatrix}$	$x = \begin{vmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{vmatrix}$ The solution is: $\begin{vmatrix} C \\ n \\ m \\ k \end{vmatrix}$
$A = \begin{vmatrix} 1 & \ln(T_{L1}) & \ln(F_1) & \ln(D_1) \\ 1 & \ln(T_{L2}) & \ln(F_2) & \ln(D_2) \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \ln(T_{L27}) & \ln(F_N) & \ln(D_N) \end{vmatrix}$	$b = \begin{vmatrix} ln(V_1) \\ ln(V_2) \\ \cdots \\ \vdots \\ ln(V_N) \end{vmatrix}$	$= \begin{vmatrix} \exp(x_1) \\ x_2 \\ x_3 \\ x_4 \end{vmatrix}$

Results of the parameter estimation can be obtained from the unknown vector x as in Table 5;

Table 5: Converting to the original parameters of the eqn. 2

n	m	k	C
x_2	x_3	x_4	$exp(x_1)$

The matrix A has dimension of (m x n) where m > n and B is a vector of m components and A is often referred to as a skinny matrix. There the number of equations is more than the number of variables, therefore the solution to the overdetermined system of equations AX = B can be determined using the linear least squares. Therefore, we search for the solution which satisfy ($Ax \approx B$), that means Ax is closed to B in a norm-square sense. The solution x that minimizes ($||Ax - B||_2$). The analytical solution can be obtained by setting the gradient of $||Ax - B||^2$ with respect to x to zero. By arranging the system of linear equations yields $A^T(Ax - B) = 0$, also can be simplified to $A^T B - A^T A\, x = 0$, or $A^T A\, x = A^T B$. Then the solution can be obtained from $x = (A^T A)^{-1} A^T B$. This is the linear least squares abroach. When using MATLAB [15], the solution can be simply obtained by $x = \mathrm{inv}(A.' * A) * A.' * B$.

The comparison between our estimated function of the Tool Life and the measured tool life is in Figure 4. Our data V, F, D and T_L (from Table) are arranged in a matrix A and a vector B. In order to arrange our linearized equation number 6 to the best form of the linear system of equations (A x = B), in Table 8, there are four options for these arrangements, where the right-hand side vector B and the matrix A should give the same results.

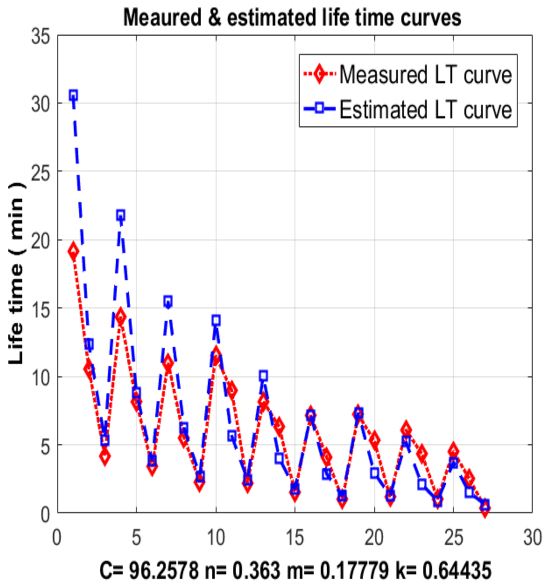


Fig. 4: Measured versus Estimated Tool life

However, by including one of the controlled parameters such as cutting speed (V), on the right-hand-side of the system of linear equations, the solution was affected by tool life measurement error. One way to investigate of how accurate is the measured data (the right-hand side), is to use each of the controlled parameters (V, F, and D) as (the right-hand-side). Meanwhile, integrate the Tool life measurement term (T_L) in the (left-hand-side). Then set up a linear system of equations and solving using linear least squares. The results should be independent of how we arrange the controlled parameters and tool life measurements between left- and right-hand-side. if there are no tool life measurement errors. In order to check the sensitivity of the linearized model to errors associated with collecting the measured tool life, we test four arrangements of equation 6. All four possible arrangements of the vector B and matrix A of the system A x = b, are illustrated in Table 8, where we specify the equation to be solved, unknown parameters, Figures of the fitting, and the results for each arrangement of the vector B. Error associated with tool life measurements can be clearly seen when we arrange equation nr. 6 to all four possible forms as indicated in Table 8. Here is the second arrangement of the vector B and the matrix A, as clarified in Table 6 & 7, and the estimated parameters in Figure 5.

Table 6: Parameters for the linear system of equations (case b)

Known parameters from table 1 ($1 \le i \le 27$)				
b_i	a_{i1}	a_{i2}	a_{i3}	a_{i4}
$ln(T_{L_i})$	1	$-ln(V_i)$	$-ln(F_i)$	$-ln(D_i)$
Unknown parameters				
	x_1	x_2	x_3	x_4
	$ln(C)/n$	$1/n$	m/n	k/n

Table 7: Converting to the original parameters of the eqn. 2

n	m	k	C
$1/x_2$	x_3/x_2	x_4/x_2	$exp(x_1/x_2)$

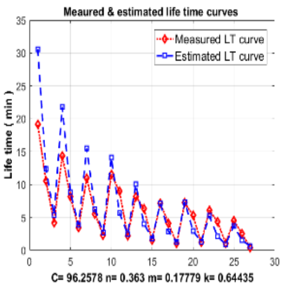
Table 8: Possible of right side of the system of linear equations

Arrangement 1 of Ax=b: (B vector includes controlled V parameter) Equation nr. 6 and solving for right hand side of $ln(V)$

$$a_{i1}x_1 - a_{i2}x_2 - a_{i3}x_3 - a_{i4}x_4 = b_i \quad (1 \le i \le 27)$$

$$\overbrace{\ln(C)}^{x_1} - \overbrace{\hat{n}}^{x_2}\,\overbrace{\ln(T_L)}^{a_{i2}} - \overbrace{\hat{m}}^{x_3}\,\overbrace{\ln(F)}^{a_{i3}} - \overbrace{\hat{k}}^{x_4}\,\overbrace{\ln(D)}^{a_{i4}} = \overbrace{\ln(V)}^{b_i}$$

(a)

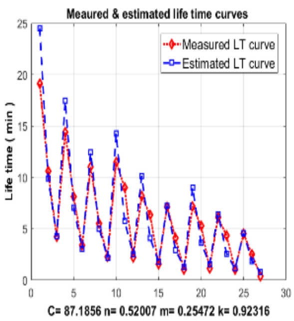


Arrangement 2 of Ax=b: (B vector includes measured T_L results) Dividing equation nr. 6 by n and solving for right hand side of $ln(T_L)$

$$a_{i1}x_1 - a_{i2}x_2 - a_{i3}x_3 - a_{i4}x_4 = b_i \quad (1 \le i \le 27)$$

$$\overbrace{\frac{1}{n}\ln(C)}^{x_1} - \overbrace{\frac{\hat{1}}{n}}^{x_2}\,\overbrace{\ln(V)}^{a_{i2}} - \overbrace{\frac{\hat{m}}{n}}^{x_3}\,\overbrace{\ln(F)}^{a_{i3}} - \overbrace{\frac{\hat{k}}{n}}^{x_4}\,\overbrace{\ln(D)}^{a_{i4}} = \overbrace{\ln(T_L)}^{b_i}$$

(b)

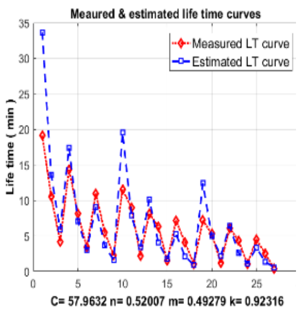


Arrangement 3 of Ax=b: (B vector includes controlled F parameter) Dividing equation nr. 6 by m and solving for right hand side of $ln(F)$

$$a_{i1}x_1 - a_{i2}x_2 - a_{i3}x_3 - a_{i4}x_4 = b_i \quad (1 \le i \le 27)$$

$$\overbrace{\frac{1}{m}\ln(C)}^{x_1} - \overbrace{\frac{\hat{1}}{m}}^{x_2}\,\overbrace{\ln(V)}^{a_{i2}} - \overbrace{\frac{\hat{n}}{m}}^{x_3}\,\overbrace{\ln(T_L)}^{a_{i3}} - \overbrace{\frac{\hat{k}}{m}}^{x_4}\,\overbrace{\ln(D)}^{a_{i4}} = \overbrace{\ln(F)}^{b_i}$$

(c)

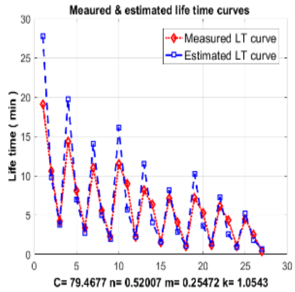


Arrangement 4 of Ax=b: (B vector includes controlled D parameter) Dividing equation nr. 6 by k and solving for right hand side of $ln(D)$

$$a_{i1}x_1 - a_{i2}x_2 - a_{i3}x_3 - a_{i4}x_4 = b_i \quad (1 \le i \le 27)$$

$$\overbrace{\frac{1}{k}\ln(C)}^{x_1} - \overbrace{\frac{\hat{1}}{k}}^{x_2}\,\overbrace{\ln(V)}^{a_{i2}} - \overbrace{\frac{\hat{n}}{k}}^{x_3}\,\overbrace{\ln(T_L)}^{a_{i3}} - \overbrace{\frac{\hat{m}}{k}}^{x_4}\,\overbrace{\ln(F)}^{a_{i4}} = \overbrace{\ln(D)}^{b_i}$$

(d)



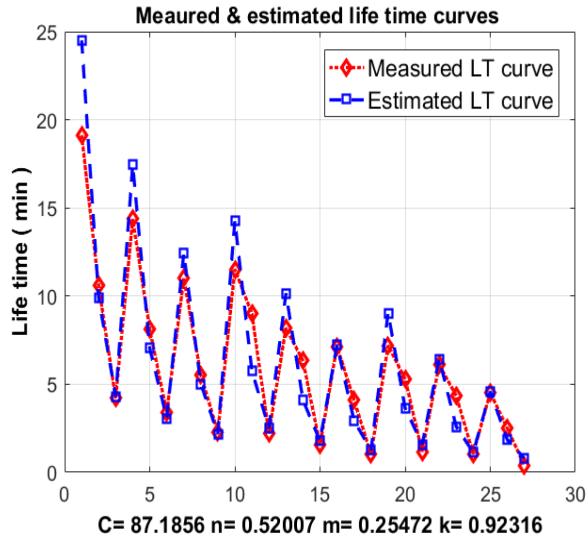


Fig. 5: Measured versus Estimated Tool life

Then errors are calculated for each of the four B vector arrangements for the 27 samples (data-i) from equation nr. 11.

$$Error(i) = B_{i=1\to 27} - \sum_{\substack{i=1\to 27 \\ j=1\to 4}}^{4} a_{ij}x_j = b_i - a_{i1}\,x_1 + a_{i2}\,x_2 + a_{i3}\,x_3 + a_{i4}\,x_4 \quad (1 \le i \le 27) \tag{11}$$

Figure 6 shows the bar plot of errors from equation 11 for four B vector arrangements and for all the 27 samples of the controlled parameters (V, F, and D) and the measured Tool life.

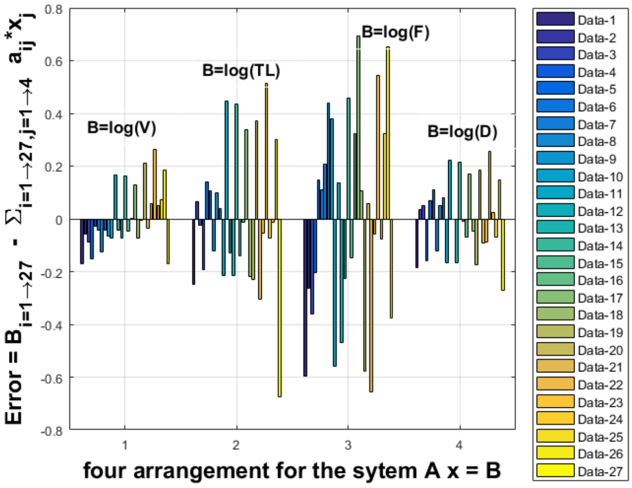


Fig. 6: Error of the four arranged system of linear equations

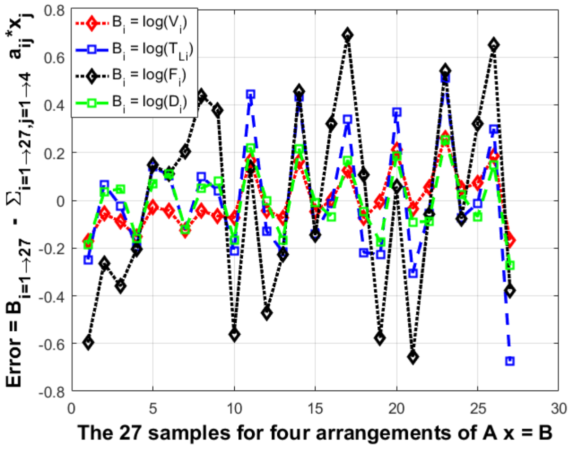


Fig. 7: Error from the four arranged system of linear equations

Figure 8 describes errors between analytical and measured tool life for each proposed solution from Table 8. As can be seen that the blue curve-line gives minimum error between measured and analytical tool life, The blue curve-line generated when B vector has the measured tool life (T_L), therefore the optimal arrangement to be solved is the second one from Table 8. The all other three controlled parameters (V, F, and D) from the 27 samples are include in the A matrix.

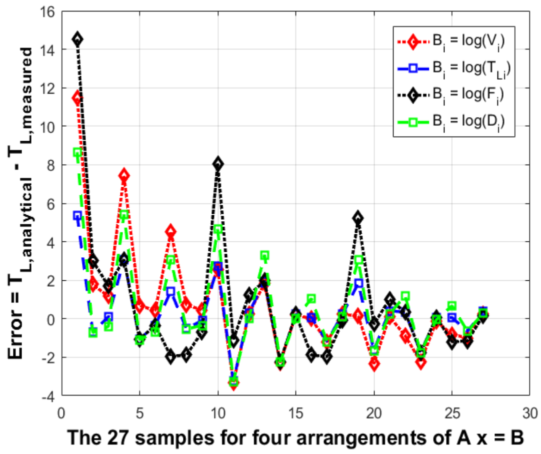


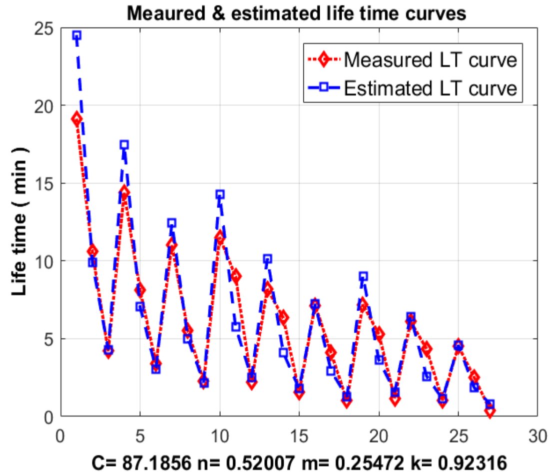
Fig. 8: Error between analytical & measured tool life for four arranged of B vector.

5. Results and Discussion

The measured tool life "column nr. 5" are shown below in figure 9 & 10.

In Figure 9, the estimated Tool Life versus the measured tool life values are plotted in the y-axis for each of the 27th experimental samples represented as the x-axis. The two curves are converged very well for the determined parameters which produce the following equation. This equation represents the end of life of an insert carbide tool to cut the medium carbide steel for the used machine for any combination of the cutting parameters.

$$V\ T_L^{0.52007}\ F^{0.25472}\ \ D^{0.92316} = 87.1856 \qquad (8)$$



Fig, 9: The estimated Tool Life versus measured Tool Life

Figure (10) shows behavior of the Tool Life for 27th combination of cutting parameters. The three cutting speeds are 92.68, 122.83 and 155.63 m/min. The three feed rates are 0.09, 0.18 and 0.36 mm/rev. The three cutting depths are 0.3, 0.5 and 0.8 mm. It is clear that the tool life decreases when speed of cut increases. The same effect is recorded for the feed rate. The cutting depth has a small impact on developing the tool life curve but in the same direction of both speed of cut and feed rate. Also, it is clear that the maximum life obtained with minimum speed of cut, minimum feed rate and minimum cutting depth. The shortest tool life was found at a high combination of speed of cut, feed rate and cutting depth.

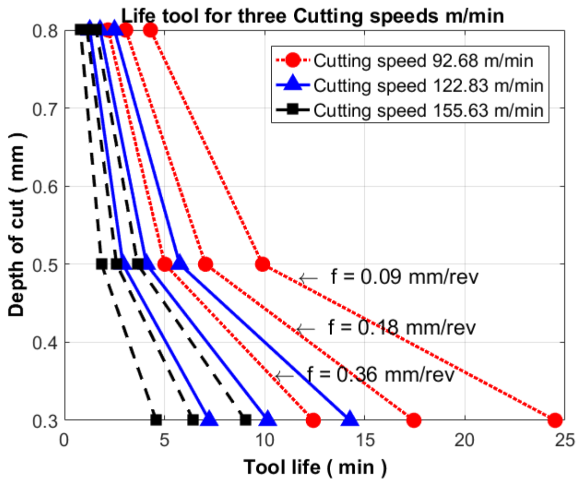


Fig. 10: The effects of cutting parameters on the tool life eqn. 8.

Figure 11 shows the cutting temperatures evaluated using Nathan Cook form [14] for turning machine. The red circle-ball dotted curve performed at 92.68 m/min and three cutting depths of 0.3, 0.5 and 0.8 mm. The blue triangles line curve for speed of cut of 122.83 m/min plotted for the three cutting depths, while the black square-dashed curve for speed of cut of 155.63 m/min are plotted for the same three cutting depths. The tool chip temperature increases as the depth of cut increases. The cutting temperature increases when the speed of cut increases. An increase of 0.2 in the cutting depth caused an increase in the cutting temperature around 160 % while a 30 m/min increase in the speed of cut caused an increase in the cutting temperature about 80 %. Therefore, the cutting depth influences the cutting temperature double of what the speed of cut does. Figure 12 shows an approximation of the Tool life as a function of the cutting temperature using Nathan Cook form [14] and the estimated Taylor expanded equation, it is clear that high cutting temperatures cause short Tool life values. These short Tool life values were documented at high cutting speeds.

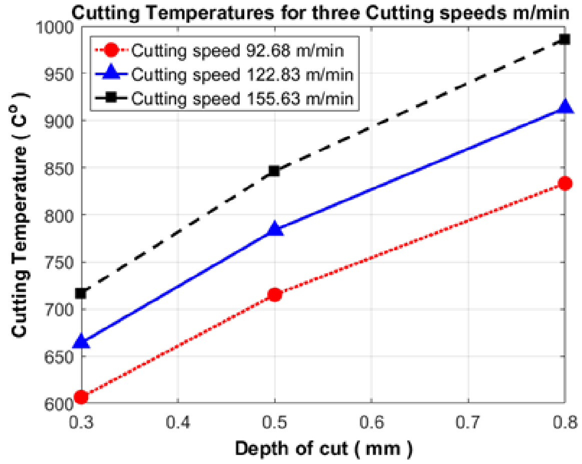


Fig. 11: The approximated temperature rises at tool chip interface based on the Nathan Cook model from eqn. 3.

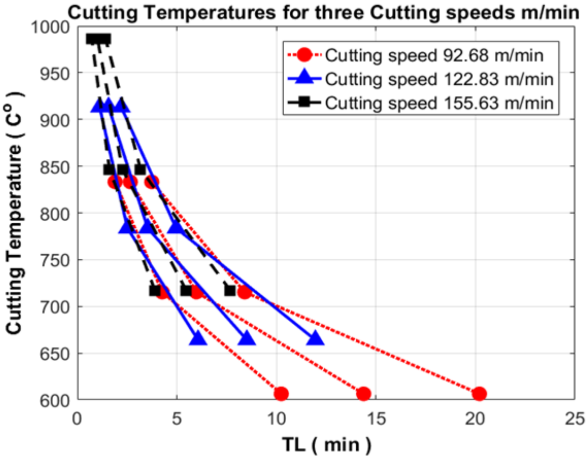


Fig. 12. The approximated temperature rises at tool chip interface versus the Tool life from eqn. 4.

6. Conclusion

The set of experiments has been performed at dry condition for different machine speed that is 92.68 m/min 122.83 m/min, and 155.63 m/min. Here, in the research work we have considered different feed rates 0.09, 0.18, 0.36 mm/rev, and cutting depth of 0.3, 0.5, 0.8 mm. The points that have been concluded from the experiment are that during the turning process, the cutting edge was subjected to great stresses, as a result of its penetration into the metal. The removal part of the metal surface in the form of chip and the temperature rise can be controlled by implementing set of optimal cutting parameters. The critical cutting parameters produce poor surface finish of the workpiece and tool wear. Then the cutting tool must be disassembled and sharpened or replaced with another. That causes an increase in the cost and production time. To maintain the cutting tool for longer tool life, the appropriate operating conditions must be used for the operation process. In this study, the tool life was measured and estimated, then a clear explanation was provided for the effect of cutting parameters on the tool life of an insert carbide tool. The insert carbide tool used in a longitudinal turning of C-45 medium carbide steel. By varying the speed of cut, feed rate and cutting depth, the tool life was calculated. For best turning tool life, it is necessary to reduce the speed of cut (reduce cutting temperature), and optimize the feed rate and cutting depth. The speed of cut shows the largest influence on the tool life among other cutting parameters therefore it should be adjusted for best economical value. In the future work, the nonlinear least squares will be used to predict parameters of the expanded Taylor tool life equation, instead of linearizing the ETTL equation. That will reduce the effect of any uncounted errors during collecting Tool life times. It is also important to include the measured Tool life in the right-hand side of the linearized modified Taylor's equation since tool life measurements are mostly contaminated by measurement error.

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