Development of Mathematical Cost Model for Room Temperature End-milling of AISI D2 Tool Steel

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Abstract

In this research paper, reliable mathematical model for estimating the cost of room temperature end-milling of AISI D2 tool steel using TiAlN coated carbide tool inserts is developed. Initially, the different components of machining cost were identified, followed by establishment of equations to determine their values. Then, the required experimental and non-experimental data were collected and the bottom-up approach was adopted for evaluating the cost of machining corresponding to each of fifteen experimental runs. The Response Surface Methodology (RSM) was used to develop the model in which the cost of machining is given as a function of the machining parameters; cutting speed, feed per tooth, and depth of cut, and expressed in RM per cm^3. ANOVA output was utilized to check the adequacy of the developed model. The developed model was found to be statistically adequate and this was confirmed by the small prediction errors made by the model.

Keywords: machining cost, cost modeling, room temperature end-milling, RSM, AISI D2 tool steel.

1.0 Introduction

Advances in machine tool and cutting tools have allowed machining of hardened steels to become more spread in manufacturing processes, and to become a realistic replacement for many grinding operations [1].

With the advancement of technology, the problems of cost estimation, cost analysis and cost control have assumed great dominance in economic and engineering decisions. These factors are highly critical for the continued success of a manufacturing enterprise [2]. Cost estimates have several significant uses such as: to provide information to be used in establishing the selling prices [3]

Development of reliable cost models to estimate the cost of room temperature machining of AISI D2 tool steel at different levels of machining parameters; cutting speed, feed, and depth of cut, is a useful endeavor. Having cost models enables determining which cost elements contribute most to the cost; i.e. it can identify cost drivers. With cost model it is possible to determine the conditions that minimize cost (cost optimization).

In this research paper, the bottom-up and parametric cost estimation techniques were merged to develop a rather new technique that is free from the limitations of the parent techniques and inherits their advantages. The bottom-up and parametric cost estimation techniques are the most common in practice. They are the two main techniques from which several other techniques branch out [4].

The cost models found in the literature that can be used for estimating the cost of a machining run are generally less use-friendly, and do not combine between accuracy and user-friendliness. These problems, through merging the bottom-up and parametric techniques, and modeling the cost of machining as a function of a small number of parameters for which data can be obtained rather easily, are efficiently solved.

2.0 Overview of Past Machining Cost Models

The past models of machining cost are generally descriptive; that is, they describe the cost components found in machining operations. This characteristic causes two problems: firstly, the model will be consisting of parameters for some of which data is not easy to obtain. Secondly, it will be consisting of many input parameters. Thus, it is not user-friendly. For instance, George E. D. [5] presented the following cost model which can be used to calculate the cost of an end-milling operation:

$$C_u = \frac{1}{60}\left[\frac{M(1+OH_m)}{100} + \frac{W(1+OH_{op})}{100}\right]\left[t_m(1+\frac{t_{tool}}{T}) + t_0\right] + C_t\frac{t_m}{T} \quad (1)$$

where

C_u = total unit cost, $ M = machine cost (profit, depreciation, and maintenance), $/h
OH_m = machine overhead (power, proportional share of building, taxes, insurance, etc), %
W = labor rate for operator, $/h OH_{op} = operator overhead rate, %
t_m = machining time t_{tool} = tool changing time T = tool life
t_0 = time elements that are independent of tool life C_t = tool cost, $

Obviously, this model is not user friendly for finding the cost of a particular operation (or a run). It contains of around ten input parameters for which the user has to find data. Besides containing many input parameters, data for some of these input parameters are not easily obtainable. For instance, any particular value of tool life is accompanied with a particular value of consumed power. Obtaining data on this pair is not readily easy.

The model developed in this paper contains only three input parameters. The values for these parameters are chosen by the user (independent), unlike power and tool life (as mentioned earlier) which are dependent on each other. Besides being a user-friendly model, it gives rather accurate estimations.

Similar models (to the one presented by George E. D.) were proposed by Robert C. C. et al. [3], Gavriel S. [6], Geoffrey B. and Winston A. K. [7], and others.

3.0 Research Methodology

The methodology of this research can be outlined in form of the following activities:

- Establishment of equations to evaluate the cost of removing a unit volume of material (RM per cm^3).
- Collection of all the data (experimental and non-experimental) required for evaluation of machining cost.
- Evaluation of machining cost considering 25% utilization level.
- Use of RSM to model the cost of machining. ANOVA tables were used to check the adequacy of the developed model.

3.1 Establishment of Equations for Evaluating the Cost of Machining

In this research paper, the cost of machining is made up by the following cost components: operator cost, VMC depreciation cost, VMC maintenance cost, cost of electricity consumed by the VMC, tool edge cost, tool edge changing cost, and setup, loading, unloading, and teardown (SLUT) cost [3, 5, 6, 7].

Machining cost was determined in terms of cost required to remove a unit volume of material (RM per cm^3). Rather than evaluating the cost per component, determination of cost per unit volume of removed material can be more appropriate approach. Machining cost was evaluated considering a 25% utilization level. This level of utilization is used in process-based facilities (e.g. job-shops). To reduce the truncation error, a long period (a span of one year) of production has been chosen for the calculation of machining cost.

During production time, the following activities are carried out: machine setup, work-piece loading, material removing, tool changing, work-piece unloading, and machine teardown. At 25% utilization, the production time per 8-hours working day is 120 minutes (8 * 60 * 0.25). Out of these 120 minutes, 15 are used for setup, loading, unloading, and teardown (SLUT). These 15 minutes are equivalent to 3.125% ((15 / (8 * 60)) * 100) of the working day. The remaining production time in the day at 25% utilization level is (120 - 15) = 105 minutes. These 105 minutes are equivalent to 21.875% (25% - 3.125%) of the 8-hours working day. These 105 minutes are used for material removing and tool changing only.

Table 1 presents the equations that were established to determine the values of the machining cost components.

Table 1: Components of machining cost and the equations established to determine their values

Cost Component	Equation
Operator Cost	$\textbf{Operator Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right)=\left(\text{Operator's Salary per Year}\left(\frac{\text{RM}}{\text{yr}}\right)\right)/\left(\text{VMR per Year}\left(\frac{\text{cm}^3}{\text{yr}}\right)\right)$
VMC Depreciation Cost	$\textbf{VMC Depreciation Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right)=\left(\text{VMC Annuity}\left(\frac{\text{RM}}{\text{yr}}\right)\right)/\left(\text{VMR per Year}\left(\frac{\text{cm}^3}{\text{yr}}\right)\right)$
VMC Maintenance Cost	$\textbf{VMC Maintenance Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right)=\left(\text{VMC Maintenance Cost per Year}\left(\frac{\text{RM}}{\text{yr}}\right)\right)/\left(\text{VMR per Year}\left(\frac{\text{cm}^3}{\text{yr}}\right)\right)$
Cost of Electricity Consumed by the VMC	$\textbf{VMC Electricity Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right)=\left(\text{Electricity Consumed by the VMC per Hour}\left(\frac{\text{RM}}{\text{hr}}\right)\right)/\left(\text{MRR}\left(\frac{\text{cm}^3}{\text{hr}}\right)\right)$
Tool Edge Cost	$\textbf{Tool Edge Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right)=\left(\text{Cost per Tool Edge (RM)}\right)/\left(\text{Tool Life}\left(\text{min}\right)*\text{MRR}\left(\frac{\text{cm}^3}{\text{min}}\right)\right)$
Tool Edge Changing Cost	$\textbf{Tool Edge Changing Cost per cm}^3\left(\frac{\text{RM}}{\text{cm}^3}\right)=\frac{\text{Tool Edge Changing Time}\left(\text{min}\right)*\left(\text{Operator Cost per min}\left(\frac{\text{RM}}{\text{min}}\right)+\text{Machine Cost per min}\left(\frac{\text{RM}}{\text{min}}\right)\right)}{\text{Tool Life}\left(\text{min}\right)*\text{MRR}\left(\frac{\text{cm}^3}{\text{min}}\right)}$
Setup, Loading, Unloading, and Teardown (SLUT) Cost	$\textbf{Setup, Loading \& Unloading and Teardown Cost per cm}^3\left(\frac{\text{RM}}{\text{cm}^3}\right)=\frac{\text{SLUT Time}\left(\text{min}\right)*\left(\text{Operator Cost per min}\left(\frac{\text{RM}}{\text{min}}\right)+\text{Machine Cost per min}\left(\frac{\text{RM}}{\text{min}}\right)\right)}{\left(\frac{\left(8*60*\text{K}\right)\left(\text{min}\right)}{\text{Tool Life}+\text{Tool Edge Changing Time (min)}}\right)*\text{Tool Life}\left(\text{min}\right)*\text{MRR}\left(\frac{\text{cm}^3}{\text{min}}\right)}$

The volume of material removed per year (VMR per year) considered in some of the equations that are presented in Table 1 is calculated as follows:

$$\text{VMR per Year}\left(\frac{\text{cm}^3}{\text{yr}}\right)=\left(250*8*60*\text{K}\left(\frac{\text{min}}{\text{yr}}\right)/\left(\left(\text{Tool Life}+\text{Tool Changing Time}\right)\left(\text{min}\right)\right)\right)*\text{Tool Life}\left(\text{min}\right)*\text{MRR}\left(\frac{\text{cm}^3}{\text{min}}\right)$$

where, K = 0.21875 (the level of utilization available for material removing and tool changing only).

The Annuity is calculated as follows:

$$\text{Annuity}\left(\frac{\text{RM}}{\text{yr}}\right)=\text{P}*(\text{i}\,(1+\text{i})^{\text{n}}/((1+\text{i})^{\text{n}}-1))$$

where, P = initial expenses of the VMC i = cost of capital (%) n = useful life of the VMC

Operator cost per minute is given by the following equation:

$$\textbf{Opertaor Cost per Minute}\left(\frac{\textbf{RM}}{\textbf{min}}\right)=\left(\text{Operator's Cost per Year}\left(\frac{\text{RM}}{\text{yr}}\right)\right)/\left(250*8*60*\text{Utilization}\left(\frac{\text{min}}{\text{yr}}\right)\right)$$

The machine cost per minute is given by the following equation:

$$\textbf{Machine Cost per Minute}\left(\frac{\textbf{RM}}{\textbf{min}}\right)=$$

$$\frac{\text{VMC Annuity}\left(\frac{\text{RM}}{\text{yr}}\right)+\text{VMC Maintenance Cost per Year}\left(\frac{\text{RM}}{\text{yr}}\right)}{250*8*60\ \text{Utilization}\left(\frac{\text{min}}{\text{yr}}\right)}+\text{Electricity Consumed by VMC per Minute}\left(\frac{\text{RM}}{\text{min}}\right)$$

3.2 Data used for Evaluation of Machining Cost

The data that were used to evaluate the cost of machining fall into two categories; experimental data [8], and non-experimental data. The non-experimental data are based on realistic assumptions or estimations. For example, the number of working days per year is assumed considering a realistic situation, whereas, the tool changing time was estimated through time study conducted in the laboratory. These data are shown in Tables 2 and 3.

Table 2: The experimental data used in evaluation of machining cost

Run No.	Cutting Speed (v) (m/min)	Feed (f) (mm/tooth)	Depth of Cut (d) (mm)	Tool Life (min)	MRR (cm^3/min)	Electricity Cost per Hour (RM/hr)
1	72.28	0.025	1.63	27.83	0.1172	0.0494
2	72.28	0.079	0.61	8.81	0.1386	0.0578
3	44.27	0.079	1.63	25.16	0.2268	0.0951
4	44.27	0.025	0.61	124.93	0.0269	0.0101
5	56.57	0.044	1.00	30.30	0.0990	0.0415
6	56.57	0.044	1.00	32.50	0.0990	0.0415
7	56.57	0.044	1.00	29.50	0.0990	0.0415
8	56.57	0.044	1.00	31.70	0.0990	0.0415
9	56.57	0.044	1.00	33.90	0.0990	0.0415
10	40.00	0.044	1.00	114.27	0.0700	0.0293
11	80.00	0.044	1.00	10.71	0.1400	0.0586
12	56.57	0.044	0.50	70.70	0.0495	0.0190
13	56.57	0.044	2.00	20.20	0.1980	0.0829
14	56.57	0.020	1.00	55.55	0.0450	0.0173
15	56.57	0.100	1.00	8.89	0.2251	0.0942

Table 3: The non-experimental data used for evaluating the cost of machining

Factor	Specification
Working days per year	250
Working hours per day	8 of one shift
Utilization level	25%
Operator's salary per year	RM 33600 (RM 2800 * 12)
Initial expense of the VMC	RM 300000
Useful life of the VMC	15 years
Cost of capital (%)	5
Depreciation method	Sinking fund
Yearly expense on VMC maintenance	RM 5000
Electricity tariff	RM 0.4 per kWh
Price per edge of cutting tool	RM 15
Tool changing time	5 minutes
Setup, loading, unloading, and teardown time	15 minutes

3.3 Evaluation of Machining Cost

Machining cost was evaluated considering 25% utilization level. The results are shown in Table 4.

Table 4: Machining cost evaluated at 25% utilization level

Run No.	Operator Cost (RM/cm^3)	VMC Depreciation Cost (RM/cm^3)	VMC Maintenance Cost (RM/cm^3)	VMC Electricity Cost (RM/cm^3)	Tool Edge Cost (RM/cm^3)	Tool Edge Changing Cost (RM/cm^3)	Setup, Loading, Unloading, and Teardown Cost (RM/cm^3)	Machining Cost (RM/cm^3)
1	12.8837	11.0825	1.9172	0.0070	4.5989	3.4505	3.2366	37.1765
2	14.4765	12.4527	2.1542	0.0070	12.2843	9.2176	3.6370	54.2293
3	6.7653	5.8195	1.0067	0.0070	2.6287	1.9730	1.7001	19.9004
4	49.4881	42.5696	7.3643	0.0063	4.4635	3.3480	12.4287	119.6683
5	15.0628	12.9570	2.2415	0.0070	5.0005	3.7517	3.7838	42.8044
6	14.9184	12.8328	2.2200	0.0070	4.6620	3.4977	3.7476	41.8855
7	15.1207	13.0068	2.2501	0.0070	5.1361	3.8534	3.7984	43.1725
8	14.9686	12.8760	2.2275	0.0070	4.7797	3.5860	3.7602	42.2049
9	14.8363	12.7621	2.2078	0.0070	4.4695	3.3533	3.7269	41.3628
10	19.0858	16.4176	2.8402	0.0070	1.8753	1.4068	4.7940	46.4266
11	13.4112	11.5363	1.9957	0.0070	10.0040	7.5066	3.3694	47.8302
12	27.6873	23.8166	4.1201	0.0064	4.2861	3.2152	6.9540	70.0858
13	8.0648	6.9373	1.2001	0.0070	3.7504	2.8146	2.0265	24.8008
14	31.0047	26.6702	4.6138	0.0064	6.0006	4.5012	7.7871	80.5840
15	8.8845	7.6425	1.3221	0.0070	7.4957	5.6260	2.2327	33.2105

The machining parameters and their values that are presented in Table 2 are the factors (variables) in modeling the machining cost, while the machining cost values that are presented in the last column of Table 4 is the response.

4.0 Results and Discussion

The Response Surface Methodology (RSM) was used for developing the model. The software Design-Expert 6.0.8 was utilized for this purpose. In the developed model, machining cost is expressed in terms of the machining parameters; cutting speed (v), feed per tooth (f), and depth of cut (d).

Analysis of variance (ANOVA) was used to test the adequacy of the developed model. The adequacy was verified at 95% confidence interval. ANOVA output includes statistics such as "Prob > F" and "lack of fit" values. These were used to examine the significance of the model and its terms. "Prob > F" value that is less than 0.05 generally indicates significance at 95% confidence interval. If it is greater than 0.05, this generally indicates insignificance. Various types of R^2 were used to examine the prediction capability of the developed model. Higher values of R^2 indicate that the model is capable of explaining higher percentages of variability in the response. The adequacy of the developed model was confirmed by comparing the actual and predicted values of cost.

4.1 Formulation of Mathematical Model and Checking of Adequacy

Model 1 was developed for estimating the cost of machining (RM per cm^3) in room temperature end-milling of AISI D2 tool steel at 25% utilization level using TiAlN coated carbide inserts.

$$\mathbf{Log_{10}(Machining\ Cost)} = +\,3.64099 - 0.020173 * v - 32.94624 * f - 0.66055 * d + 1.12909\text{E-}004 * v^2 + 121.20438 * f^2 + 0.13445 * d^2 + 0.19413 * v * f - 1.61009\text{E-}003 * v * d + 2.59869 * f * d$$

Model 1

The ANOVA output of Model 1 (shown in Table 6) indicates that this Model is statistically significant and fitting for exploring the design space at 95% confidence interval.

Table 6: ANOVA output of Model 1

Source	P-value (Prob > F)	Remark
Model	< 0.0001	*Significant*
Term	All the terms have P-values less than 0.05 except "AC"	*Significant*
Lack of fit	0.4866	*Not Significant*
R-Squared	0.9995	
Adj. R-Squared	0.9986	
Pred. R-Squared	0.9915	

The "Prob > F" values of the Model and its "Lack-of-Fit" which are "< 0.0001" and 0.4866, respectively, prove that the Model is statistically adequate.

All the terms of the model (except the term AC) are significant at the 95% confidence interval as indicated by their "Prob > F" values which are all less than 0.05. The term AC is not significant, as indicated by its "Prob > F" value which is greater than 0.05. This term has been included in the Model because its removal adversely affects the adequacy of the model.

The "Pred R-Squared" of 0.9915 is in reasonable agreement with the "Adj R-Squared" of 0.9986 (within 0.2 from each other); this indicates that there is no problem; neither with the data nor with the Model. The "R-squared" value of 0.9995 indicates that the Model reasonably explains 99.95% of the variability of the machining cost.

4.2 Adequacy Confirmation

The adequacy of the developed model was confirmed by comparing the actual costs that have been obtained using the cost components equations with the predicted costs that have been obtained using the developed model. The results are shown in Table 7.

All the errors made by the model, as shown in Table 7, are less than 5%. This reasonably confirms the adequacy of the developed model as indicated by the ANOVA output.

Table 7: Adequacy confirmation for the developed model

Run No.	**Cutting Speed (m/min)**	**Feed (mm/tooth)**	**Depth of Cut (mm)**	**Actual C_M (RM/cm^3)**	**Predicted C_M (RM/cm^3)**	**Error (%)**
1	72.28	0.025	1.63	37.1765	37.3579	**0.49**
2	72.28	0.079	0.61	54.2293	54.4867	**0.47**
3	44.27	0.079	1.63	19.9004	19.9897	**0.45**
4	44.27	0.025	0.61	119.6683	120.0625	**0.33**
5	56.57	0.044	1.00	42.8044	42.3168	**1.14**
6	56.57	0.044	1.00	41.8855	42.3168	**1.03**
7	56.57	0.044	1.00	43.1725	42.3168	**1.98**
8	56.57	0.044	1.00	42.2049	42.3168	**0.27**
9	56.57	0.044	1.00	41.3628	42.3168	**2.31**
10	40.00	0.044	1.00	46.4266	46.2646	**0.35**
11	80.00	0.044	1.00	47.8302	47.5946	**0.49**
12	56.57	0.044	0.50	70.0858	69.8748	**0.30**
13	56.57	0.044	2.00	24.8008	24.6929	**0.44**
14	56.57	0.02	1.00	80.5840	80.3744	**0.26**
15	56.57	0.1	1.00	33.2105	33.0697	**0.42**

5.0 Conclusion

In this research paper, reliable mathematical model to estimate the cost of end-milling AISI D2 tool steel using TiAlN coated carbide inserts is developed. This model was developed based on 25% utilization level. The ANOVA output indicated that the model is statistically adequate and this was confirmed by the small prediction errors that are made by the model. This model is quite reliable, however, it has to be used under the conditions that have been considered in developing it, such as the level of utilization, VMC initial expenses, operator's salary, and so on. This model can be used in cost reduction programs, process selection, and establishment of selling prices.

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