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

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Abstract

In this research paper, reliable mathematical model for estimating the cost of preheated 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 preheating temperature, 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, preheated end-milling, RSM, AISI D2 tool steel.

1.0 Introduction

AISI D hardened steel group is widely used in making moulds and dies for fabrication of automotive and aerospace components [1]. Cost estimation, cost analysis and cost control are highly critical factors for the continued success of a manufacturing enterprise [2].

Development of reliable cost models to estimate the cost of preheated machining of AISI D2 tool steel at different levels of machining parameters; cutting speed, feed per tooth, and preheating temperature, is a useful endeavor. Having cost models enables determining which cost elements contribute most to the cost. 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 mathematical 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 machining run. It contains around ten input parameters for which the user has to find data. Beside this, data for some of these input parameters are not easily obtainable. The model developed in this paper contains only three input parameters; cutting speed, feed per tooth, and preheating temperature. The values for these parameters are quite easy to be obtained. Besides being a user-friendly model, it gives accurate estimations (under the specific conditions considered).

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 for evaluating 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, and ANOVA output to check the adequacy of the 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, heating device depreciation cost, VMC maintenance cost, heating device maintenance cost, cost of electricity consumed by the VMC, cost of electricity consumed by the heating device, tool edge cost, tool edge changing cost, and setup, loading, unloading, and teardown (SLUT) cost [3, 5, 6, 7].

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

Machining cost was expressed in RM per cm^3; this is more useful than evaluating the cost per component. The cost was evaluated considering 25% utilization level. This level of utilization can be found in process-based facilities (job-shops, etc). 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, 24 are used for setup, loading, unloading, and teardown (SLUT). These 24 minutes are equivalent to 5% ((24 / (8 * 60)) * 100) of the working day. The remaining production time in the day at 25% utilization level is (120 - 24) = 96 minutes. These 96 minutes are equivalent to 20% (25% - 5%) of the 8-hours working day. These 96 minutes are used for material removing and tool changing only.

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	$\textbf{VMC Electricity Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right) = \left(\text{Electricity Consumed by the VMC per Hour}\left(\frac{\text{RM}}{\text{hr}}\right)\right) / \left(\text{MRR}\left(\frac{\text{cm}^3}{\text{hr}}\right)\right)$
Heating Device (HD) Depreciation Cost	$\textbf{HD Depreciation Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right) = \left(\text{HD Annuity}\left(\frac{\text{RM}}{\text{yr}}\right)\right) / \left(\text{VMR per Year}\left(\frac{\text{cm}^3}{\text{yr}}\right)\right)$
HD Maintenance Cost	$\textbf{HD Maintenance Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right) = \left(\text{HD Maintenance Cost per Year}\left(\frac{\text{RM}}{\text{yr}}\right)\right) / \left(\text{VMR per Year}\left(\frac{\text{cm}^3}{\text{yr}}\right)\right)$
Cost of Electricity Consumed by the HD	$\textbf{HD Electricity Cost per cm}^3\left(\frac{\textbf{RM}}{\textbf{cm}^3}\right) = \left(\text{Electricity Consumed by the HD per Hour}\left(\frac{\text{RM}}{\text{hr}}\right)\right) / \left(\text{MRR}\left(\frac{\text{cm}^3}{\text{hr}}\right)\right)$
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:

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

where, K = 0.20 (the level of utilization available for material removing and tool changing only).

The Annuity is calculated as follows:

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

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

Operator cost per minute is given by the following equation:

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

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

$$\textbf{Machine cost per minute}\left(\frac{\textbf{RM}}{\textbf{min}}\right) =$$

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

$$\text{Electricity Consumed by the VMC per Minute}\left(\frac{RM}{min}\right) + \text{Electricity Consumed by the HD per Minute}\left(\frac{RM}{min}\right)$$

3.2 Data used for Evaluating the Cost of Machining

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 were obtained based on realistic assumptions or estimations. These data are shown in Tables 2 and 3.

Table 2: The non-experimental data used for evaluating the cost of machining

Factor	Specification
Working days per year	250
Working hours per day	8; one shift per day
Utilization level	25%
Operator's salary per year	RM 33600 (RM 2800 * 12)
Initial expense of the VMC	RM 300000
Initial expense of the heating device	RM 6700
Useful life of the VMC	15 years
Useful life of the heating device	7 years
Cost of capital (%)	5
Depreciation method	Sinking fund
Yearly expense on VMC maintenance	RM 5000
Yearly expense on heating device maintenance	RM 500
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	24 minutes

Table 3: The experimental data used in evaluation of machining cost

Run No.	Cutting Speed (v) (m/min)	Feed (f) (mm/tooth)	Preheating Temp. (θ) ($^{\circ}$C)	Tool Life (min)	MRR (cm^3/min)	VMC Electricity Cost per Hour (RM/hr)	HD Electricity Cost per Hour (RM/hr)
1	72.28	0.025	413	38.26	0.0719	0.0260	0.1172
2	72.28	0.079	273	11.67	0.2272	0.0932	0.1072
3	44.27	0.079	413	56.25	0.1391	0.0548	0.1304
4	44.27	0.025	273	73.82	0.0440	0.0166	0.084
5	56.57	0.044	335	95.95	0.0990	0.0398	0.104
6	56.57	0.044	335	80.8	0.0990	0.0398	0.104
7	56.57	0.044	335	78.28	0.0990	0.0398	0.104
8	56.57	0.044	335	85.85	0.0990	0.0398	0.104
9	56.57	0.044	335	84.34	0.0990	0.0398	0.104
10	40.00	0.044	335	121.41	0.0700	0.0282	0.1008
11	80.00	0.044	335	22.85	0.1400	0.0563	0.1132
12	56.57	0.044	250	85.85	0.0990	0.0406	0.0876
13	56.57	0.044	450	119.43	0.0990	0.0382	0.1268
14	56.57	0.020	335	99.99	0.0450	0.0166	0.0972
15	56.57	0.100	335	18.82	0.2251	0.0905	0.1228

3.3 Machining Cost Evaluated at 25% Utilization Level

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)	Heating Device Depreciation Cost (RM/cm^3)	VMC Maintenance Cost (RM/cm^3)	Heating Device Maintenance Cost (RM/cm^3)	VMC Electricity Cost (RM/cm^3)	Heating Device 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	22.0161	18.9382	0.7587	3.2762	0.3276	0.0060	0.0272	5.4528	4.1945	9.0728	64.0701
2	8.8021	7.5715	0.3033	1.3098	0.1310	0.0068	0.0079	5.6573	4.3537	3.6288	31.7723
3	10.9593	9.4272	0.3777	1.6309	0.1631	0.0066	0.0156	1.9171	1.4752	4.5177	30.4903
4	33.9733	29.2238	1.1708	5.0556	0.5056	0.0063	0.0318	4.6181	3.5514	13.9959	92.1325
5	14.8783	12.7983	0.5127	2.2140	0.2214	0.0067	0.0175	1.5791	1.2147	6.1313	39.5742
6	15.0165	12.9172	0.5175	2.2346	0.2235	0.0067	0.0175	1.8752	1.4425	6.1883	40.4394
7	15.0447	12.9414	0.5185	2.2388	0.2239	0.0067	0.0175	1.9356	1.4889	6.1999	40.6158
8	14.9650	12.8729	0.5157	2.2269	0.2227	0.0067	0.0175	1.7649	1.3576	6.1671	40.1171
9	14.9798	12.8856	0.5162	2.2291	0.2229	0.0067	0.0175	1.7965	1.3819	6.1731	40.2094
10	20.8237	17.9125	0.7176	3.0988	0.3099	0.0067	0.0240	1.7650	1.3576	8.5805	54.5961
11	12.1882	10.4843	0.4200	1.8137	0.1814	0.0067	0.0135	4.6890	3.6077	5.0237	38.4280
12	14.9650	12.8729	0.5157	2.2269	0.2227	0.0068	0.0147	1.7649	1.3575	6.1664	40.1136
13	14.7335	12.6737	0.5077	2.1925	0.2192	0.0064	0.0213	1.2687	0.9761	6.0726	38.6717
14	32.6668	28.1000	1.1257	4.8611	0.4861	0.0061	0.0360	3.3337	2.5630	13.4590	86.6384
15	7.8718	6.7713	0.2713	1.1714	0.1171	0.0067	0.0091	3.5408	2.7251	3.2456	25.7302

The machining parameters and their values that are presented in Table 3 are the factors (variables) in modeling the machining cost, while the machining cost values that are presented in the last column of Table 4 are 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 preheating temperature (θ).

Analysis of variance (ANOVA) was used to test the adequacy of the developed model. The adequacy was verified at 95% confidence interval. The "Prob > F" value was used to examine the significance of the model, its terms and "Lack-of-fit". "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 the Mathematical Model

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

$$\mathbf{Log_{10}(Machining\ Cost)} = +10.45787 - 0.38378 * v - 48.20697 * f - 1.05058E\text{-}003 * \theta + 6.50456E\text{-}003 * v^2 + 132.10388 * f^2 + 0.16574 * v * f - 2.10239E\text{-}005 * v * \theta + 0.048919 * f * \theta - 3.57881E\text{-}005 * v^3$$

Model 1

The ANOVA output of Model 1 that is shown in Table 5 indicates that this Model is statistically significant and fitting for exploring the design space at 95% confidence interval.

Table 5: ANOVA output for Model 1

Source	P-value (Prob > F)	Remark
Model	< 0.0001	*Significant*
Term	All the terms have P-values less than 0.05	*Significant*
Lack of fit	0.1046	*Not Significant*
R-Squared	0.9995	
Adj. R-Squared	0.9987	
Pred. R-Squared	N/A	

The "Prob > F" values of the Model and its Lack-of-Fit, which are "< 0.0001" and 0.1046, respectively, prove that Model 1 is statistically significant and fitting for navigating the design space at 95% confidence interval. All the terms of the Model are significant at the 95% confidence interval as indicated by their "Prob > F" values which are all less than 0.05. 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 6.

Table 6: Adequacy confirmation for the developed model

Run No.	**Cutting Speed (m/min)**	**Feed (mm/tooth)**	**Preheating Temp. (°C)**	**Actual C_M (RM/cm^3)**	**Predicted C_M (RM/cm^3)**	**Error (%)**
1	72.28	0.025	413	64.0701	64.1008	**0.05**
2	72.28	0.079	273	31.7723	31.7877	**0.05**
3	44.27	0.079	413	30.4903	30.4998	**0.03**
4	44.27	0.025	273	92.1325	92.1592	**0.03**
5	56.57	0.044	335	39.5742	40.0080	**1.10**
6	56.57	0.044	335	40.4394	40.0080	**1.07**
7	56.57	0.044	335	40.6158	40.0080	**1.50**
8	56.57	0.044	335	40.1171	40.0080	**0.27**
9	56.57	0.044	335	40.2094	40.0080	**0.50**
10	40.00	0.044	335	54.5961	54.6107	**0.03**
11	80.00	0.044	335	38.4280	38.4485	**0.05**
12	56.57	0.044	250	40.1136	40.6988	**1.46**
13	56.57	0.044	450	38.6717	39.0920	**1.09**
14	56.57	0.02	335	86.6384	86.6706	**0.04**
15	56.57	0.1	335	25.7302	25.7403	**0.04**

All the prediction errors made by the model, as shown in Table 6, are significantly less than 5%. This reasonably confirms the adequacy of the developed model as indicated by the ANOVA output.

5.0 Conclusion

In this research paper, reliable mathematical model to estimate the cost of preheated end-milling of AISI D2 tool steel using TiAlN coated carbide inserts was developed. This model was developed based on 25% utilization level. The ANOVA outputs indicated that the developed model is statistically adequate and this was confirmed by the small prediction errors (less than 5%) that are made by the model. This model is quite reliable, however, it has to be used within 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 successfully in cost reduction programs, process selection, and establishment of selling prices.

References

1. Lajis, M. A.; Mustafizul Karim, A. N.; Nurul Amin, A. K. M.; Hafiz, A. M. K.; & Turnad, L. G. (2008). Prediction of Tool Life in End Milling of Hardened Steel AISI D2. *European Journal of Scientific Research, 21* (4), 592-602.
2. Malstrom, E. M. (1984). *Manufacturing Cost Engineering Handbook*. Marcel Dekker, Inc. New York & Basel.
3. Crease, R. C., Adithan, M., & Pabla, B. S. (1992). *Estimating and Costing for the Metal Manufacturing Industries*. New York: MARCEL DEKKER, INC.
4. Toth, C. A. (2006). A Bottoms-up Approach to Cost Estimation using Parametric Inputs. Master Dissertation, College of Engineering and Technology of Ohio University.
5. Dieter, G. E. (2000). *Engineering Design: A Materials and Processing Approach* (3rd edn.). Singapore: McGraw-Hill.
6. Salvendy G. (2001). *Handbook of Industrial Engineering*. Canada: John Wiley & Sons, Inc.
7. Boothroyd, G., & Knight, W. A. (1989). *Fundamentals of Machining and Machine Tools* (2nd edn.). New York: MARCEL DEKKER, INC.
8. Lajis, M. A. (2009). Preheated Machining of Hardened Steel AISI D2 and Optimization of Parameters. Doctoral Dissertation, IIUM, Kuala Lumpur.
9. Esawi, A. M. K. & Ashby, M. F. (1998, May). Cost-Based Ranking for Manufacturing Process Selection. *Proceedings of the Second International Conference on Integrated Design and Manufacturing in Mechanical Engineering, 4,* 1001-1008.
10. Isakov, E. (2004). *Engineering Formulas for Metal Cutting*. New York: Industrial Press, Inc.
11. JR., E. R. S. (1995). *Precision Manufacturing Costing*. New York: MARCEL DEKKER, INC.
12. Sullivan, W. G., Bontadelli, J. A., & Wicks, E. M. (2000). *Engineering Economy* (11th edn.). New Jersy: Prentice-Hall, Inc.