

Development of an Empirical Model for Optimization of Machining Parameters to Minimize Power Consumption

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Abstract. The manufacturing sector consumes huge energy demand and the machine tools used in this sector have very less energy efficiency. Selection of the optimum machining parameters for machine tools is significant for energy saving and for reduction of environmental emission. In this work an empirical model is developed to minimize the power consumption using response surface methodology. The experiments are performed on a lathe machine tool during the turning of AISI 6061 Aluminum with coated tungsten inserts. The relationship between the power consumption and machining parameters is adequately modeled. This model is used for formulation of minimum power consumption criterion as a function of optimal machining parameters using desirability function approach. The influence of machining parameters on the energy consumption has been found using the analysis of variance. The validation of the developed empirical model is proved using the confirmation experiments. The results indicate that the developed model is effective and has potential to be adopted by the industry for minimum power consumption of machine tools.

1. Introduction

The contribution of industrial sector is one-half of the world's total energy consumption and in the last 60 years the consumption of energy by this sector has almost doubled [1]. The manufacturing sector under the industrial sector accounts for 37% of global energy demand [2]. Machine tools used as one of the critical and important equipments in the manufacturing sector have less than 30% efficiency [3] and the machine tools used in machining processes consumes electrical energy and create 99% environmental impact [4]. Worldwide, machine tool manufacturing is a USD 68.6 billion industry and very limited assessment of energy have been conducted for machining processes [2]. Machine tools contain a lot of motors and auxiliary devices whose energy consumption continuously varies during machining. For example, the spindle drives work near their peak power during rough cut while the energy consumption during finish cut is significantly lower.

The cutting tool characteristics (geometry, material, etc.), machine tool characteristics, different workpiece materials and different processing attributes have a strong influence on energy consumption of a machine tool. Determining the major machining parameters and their correlation with energy consumption is the foundation to proceed towards energy efficient machine tools. The optimal tool path design, choice of machining parameters and cutting tools can save up to 6-40% energy [5]. It is important to develop a model to quantify the correlation between the process parameters and energy consumption. The evolutionary growth of models between machining performance and parameters



remains an open field due to stochastic nature of machining process and advancement in the workpiece and cutting tool materials. Taguchi optimization approach, Response surface methodologies (RSM) are most widely used techniques by the researchers to develop the machining models. Sangwan and Kant [6] used RSM and genetic algorithm to develop predictive and optimization model during machining of AISI 1045 steel. The validation error for the developed model was less than 4%. Sarikaya and Gullu [7] used Taguchi method and desirability function analysis in RSM to determine the optimal values of machining parameters leading to minimum surface roughness characteristics. Li et al. [8] used Taguchi, particle swarm optimization and RSM for development of empirical models to save energy consumption. The previously published papers shows that researched have used various prediction and optimization techniques to develop empirical models [9–13].

The objective of this work is to develop an empirical model for minimizing the power consumption by optimization of machining parameters using response surface methodology during turning of AISI 6061 Aluminum with a coated tungsten carbide cutting tool.

2. Experimental Planning

The objective of work is to develop predictive and optimization empirical model due to which only three machining parameters are considered to simplify the modelling procedure. The machining parameters used as factors and their levels are shown in Table 1. The choice of machining parameters was made by taking into account the capacity/limiting cutting conditions of the available machine tool, tool manufacturer's catalogue and the values taken by researchers in the literature.

Table 1. Machining parameters used as factors and their levels

Factor	Symbol	Level 1	Level 2	Level 3
Cutting speed (m/min)	v	46.2	60	78
Feed rate (mm/rev.)	f	0.06	0.12	0.18
Depth of cut (mm)	d	0.5	0.75	1.0

A centre lathe of spindle speed of 2300 rpm and power of 5.5 kW was utilized to perform experiments in dry conditions. The TNMG 16 04 04 tungsten carbide inserts were used and tool holder PTG NR 2020 K16 having a rake angle of 7° , clearance angle of 6° and 0.4 mm nose radius was used. The specimen used is 47 mm \times 250 mm in size and made of AISI 6061 Aluminium. The set up used to measure the power consumption is shown in Kant and Sangwan [12]. The experimental results are shown in Table 2.

3. Results and Discussion

The analysis of variance (ANOVA) is used to analyze the influence of machining parameters on the power consumption. The results of ANOVA are shown in Table 3. Each factor's percentage contribution is also shown in Table 3. SS is the sum of squares of the deviations of all the observations from their mean. MS is the mean square and is obtained by dividing the sum of squares to the respective degree of freedom. F-value, which is a ratio of the regression mean square to the mean square error, is used to measure the significance of the model under investigation with respect to the variance of all the terms including the error term at the desired significance level. Usually, $F > 4$ means the change of the design parameter has a significant effect on the performance characteristic. The F-value for linear terms is above 4. The p-value or probability value is used to determine the statistical significance of results at a confidence level. In this study the significance level of $\alpha = 0.05$ is used, i.e. the results are validated for a confidence level of 95%. If the p -value is less than 0.05 then the corresponding factor has a statistically significant contribution to the performance characteristic and if the p -value is more than 0.05 then it means the effect of factor on the performance characteristic is not statistically significant at 95% confidence level. Feed rate influences the power consumption

with a contribution of 31.45%. The next contribution on power consumption comes from the cutting speed with a contribution of 26.43 % and then by depth of cut with a contribution of 25.63%. The quadratic [v^2 , f^2 , d^2] and interactions [$(v \times f)$, $(v \times d)$, $(f \times d)$] do not have statistical significance because they have much lower level of contribution and their p-value is also more than the 95% confidence level. RSM is used to develop the empirical model using the experimental data shown in Table 2. A polynomial equation is used to develop the empirical model for power consumption as a function of machining parameters. The developed mathematical model to predict power consumption (P) is:

$$P = 0.111708 - 0.00416351v - 0.796865f + 0.0190076d + 0.0000244078v^2 + 1.62037f^2 - 0.06933d^2 + 0.0123vf + 0.00299vd + 0.5444fd \quad (1)$$

The adequacy of the developed model is investigated using normal probability plot shown in figure 1. The errors are normally distributed and do not follow any particular trend.

Table 2. Experimental results for power consumption values (P)

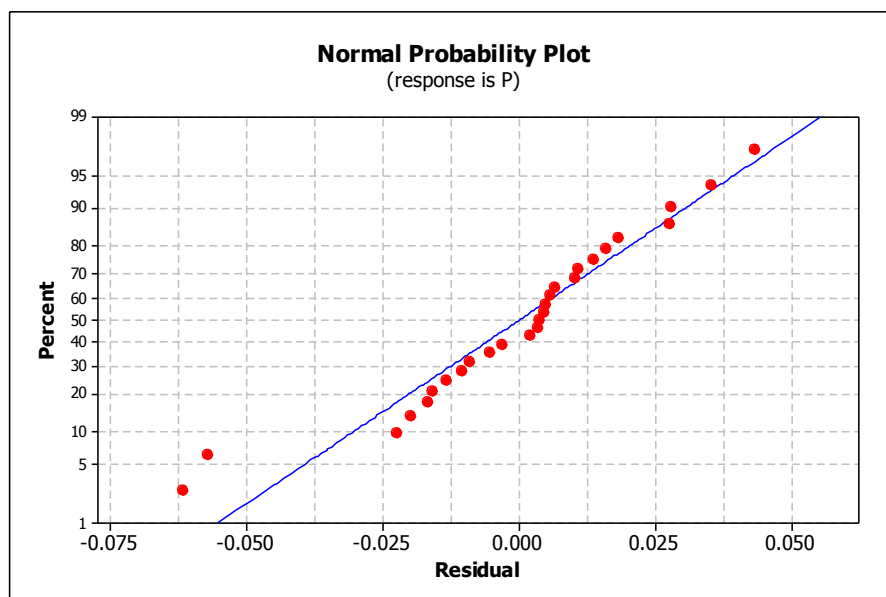
Experiment No.	v (m/min.)	f (mm/rev.)	d (mm)	P (kW)
1	46.2	0.06	0.50	0.046
2	46.2	0.06	0.75	0.095
3	46.2	0.06	1.00	0.098
4	46.2	0.12	0.50	0.039
5	46.2	0.12	0.75	0.099
6	46.2	0.12	1.00	0.059
7	46.2	0.18	0.50	0.104
8	46.2	0.18	0.75	0.140
9	46.2	0.18	1.00	0.187
10	60.0	0.06	0.50	0.037
11	60.0	0.06	0.75	0.081
12	60.0	0.06	1.00	0.116
13	60.0	0.12	0.50	0.091
14	60.0	0.12	0.75	0.122
15	60.0	0.12	1.00	0.164
16	60.0	0.18	0.50	0.107
17	60.0	0.18	0.75	0.181
18	60.0	0.18	1.00	0.235
19	78.0	0.06	0.50	0.083
20	78.0	0.06	0.75	0.106
21	78.0	0.06	1.00	0.150
22	78.0	0.12	0.50	0.111
23	78.0	0.12	0.75	0.221
24	78.0	0.12	1.00	0.262
25	78.0	0.18	0.50	0.203
26	78.0	0.18	0.75	0.184
27	78.0	0.18	1.00	0.288

The main effects of machining parameters on mean power consumption are shown in Figure 2. It reveals that power consumption increases with increase in cutting parameters. The slope of feed rate is maximum as compare to cutting speed and depth of cut, which shows that feed rate has more impact on power consumption. This trend is also supported by the ANOVA results shown in Table 3.

Table 3 ANOVA results

Source	DOF	Seq. SS	SS	MS	F	p	% Contribution
Model	9	0.1033	0.1033	0.0115	13.23	0.000	87.51
Linear	3	0.0986	0.0995	0.0332	38.22	0.000	83.51
v	1	0.0312	0.0306	0.0306	35.28	0.000	26.43
f	1	0.0371	0.0379	0.0379	43.68	0.000	31.45
d	1	0.0303	0.0310	0.0310	35.70	0.000	25.63
Square	3	0.0005	0.0005	0.0002	0.20	0.895	0.44
$v*v$	1	0.0002	0.0002	0.0002	0.24	0.629	0.18
$f*f$	1	0.0002	0.0002	0.0002	0.22	0.645	0.16
$d*d$	1	0.0001	0.0001	0.0001	0.14	0.714	0.10
Interaction	3	0.0042	0.0042	0.0014	1.61	0.223	3.56
$v*f$	1	0.0017	0.0017	0.0017	1.94	0.181	1.43
$v*d$	1	0.0017	0.0017	0.0017	1.97	0.178	1.45
$f*d$	1	0.0008	0.0008	0.0008	0.93	0.349	0.68
Residual Error	17	0.0148	0.0148	0.0009			12.49
Total	26	0.1181					
$R^2 = 0.8751$		$R^2(\text{Adj.}) = 0.8089$					

SS: Sum of square, DOF: Degree of freedom MS: Mean square

**Figure 1.** Normal probability plot of residual for power consumption

However, the results of Camposeco-Negrete (2013) while working on AISI 6061 T6 material also demonstrated that feed rate is the most significant factor and cutting speed is the least significant parameter for minimizing the total power consumption. Abhang and Hameedullah (2010) demonstrated that the feed rate has the most significant effect on power consumption, followed by depth of cut, tool nose radius and cutting speed during turning of EN-31 steel with tungsten carbide tool. Bhattacharya et al. (2009) reported that cutting speed is the most significant factor followed by depth of cut to reduce the power consumption and feed rate has no significant effect on power consumption during turning of AISI 1045 steel with coated carbide tools under high speed machining. More power is consumed due to increase in material removal rate, cutting forces and temperature. Further the power is also consumed to provide the relative movement to the cutting tool with respect to workpiece (feed rate) and rotation of spindle (cutting speed). Main effect plot clearly shows that the

mean power consumption was minimum, when the smaller values of cutting speed, feed rate and depth of cut was selected.

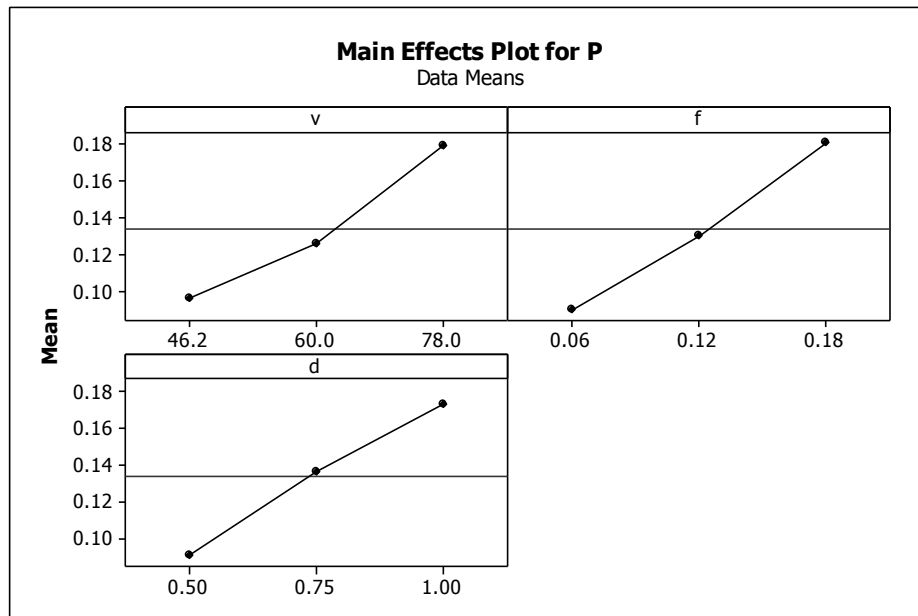


Figure 2. Main effect plot of power consumption

The 3D merged surface and contour plots for the power consumption are shown in Figure 3. Figure 3(a) shows the surface and contour plots for power consumption at 60 m/min. cutting speed. It shows that at lower values of feed rate and depth of cut, the power consumption is minimum and power consumption increases drastically with increase in depth of cut even at lower value of feed rate.

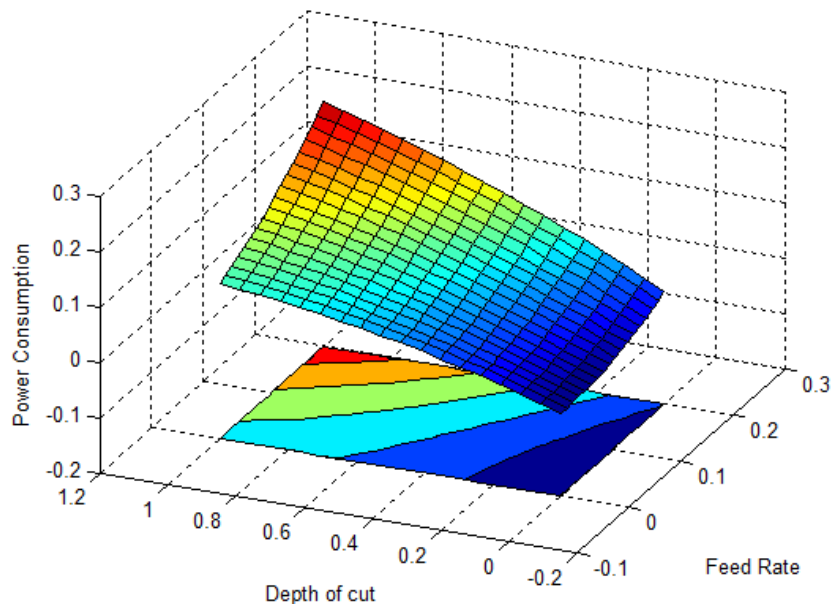


Figure. 3a. Surface plot of power consumption at fixed cutting speed

Figure 3(b) reveals that at the lower values of cutting speed and feed rate, the power consumption is minimum. Increase in cutting speed at lower values of feed rate has negligible effect on the power consumption but power consumption increases with increase in cutting speed at higher values of feed rate. Figure 3(c) indicates that power consumption is minimum at smaller values of depth of cut and

cutting speed and maximum at larger values of depth of cut and feed rate. These plots are useful to find the optimum values of cutting speed, feed rate and depth of cut for a particular value of power consumption. These 3D surface plots can be used for estimating the power consumption values for any suitable combination of the machining parameters namely cutting speed, feed rate and depth of cut. This is useful in practice for the operator or the part programmer. These plots can also be used by the machine tool designer to estimate the suitable range of parameters during the design of machine tools.

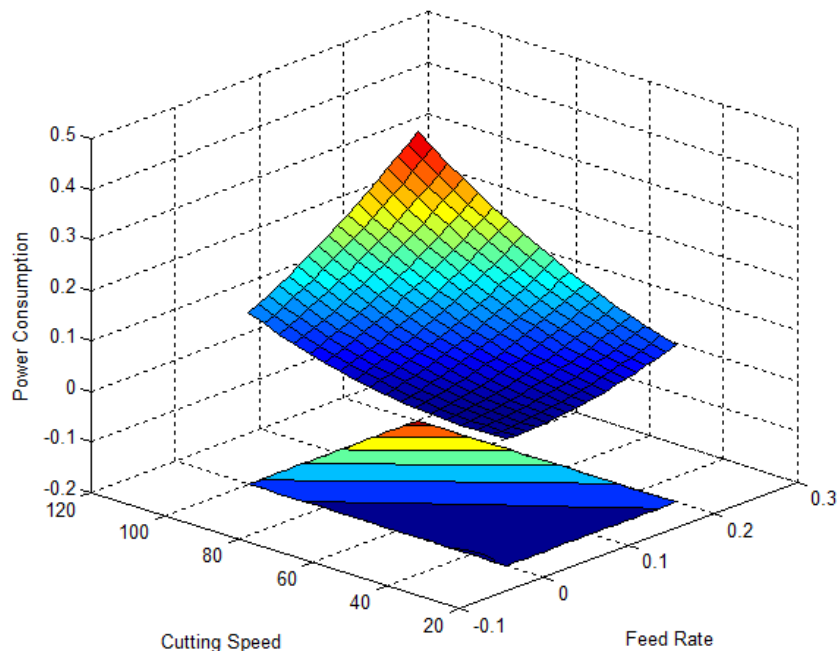


Figure 3b. Surface plot of power consumption at fixed depth of cut

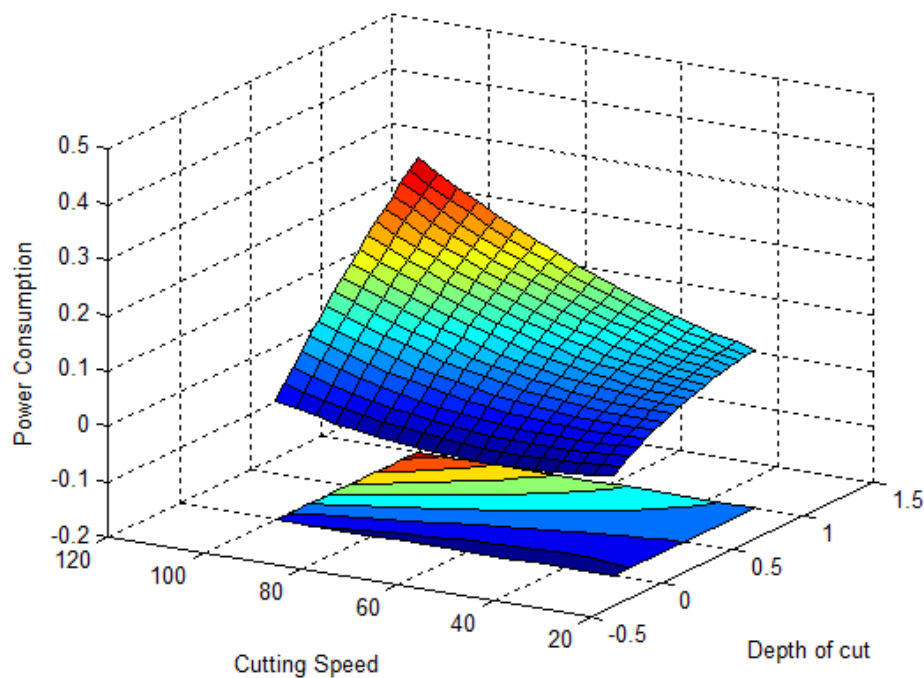


Figure 3c. Surface plot of power consumption fixed feed rate

The desirability function analysis approach is based on the reduced gradient algorithm, which starts with multiple solutions and finally obtains the maximum value of the desirability to determine the optimal solution [17]. This approach has been used for optimization of power consumption based on the empirical model given by Eq. (1). Desirability function analysis optimization results for power consumption are shown in figure 4. Optimal machining parameters obtained are shown in table 4. The optimized power consumption obtained is 0.0412 kW. The desirability value is 0.983, which is very close to 1.

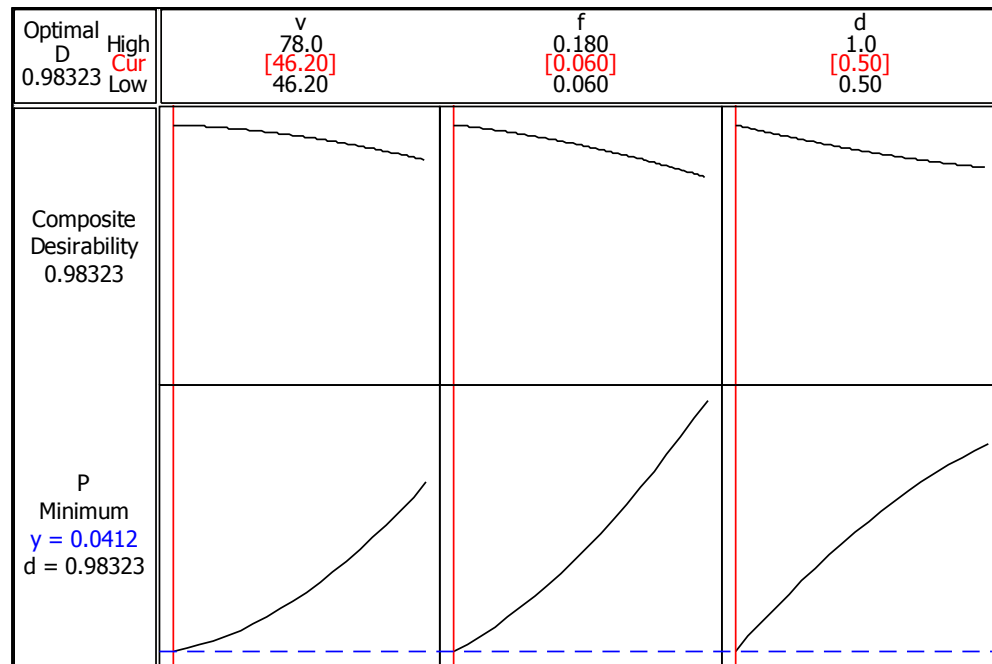


Figure 4. Power consumption optimization for machining parameters

4. Confirmation experiments

The validation experiments are performed on obtained feasible optimal machining parameters for the power consumption. The results of the validation experiments are shown in table 4. The error between the predicted and the confirmation results is 6.78%.

Table 4. Confirmation results for power consumption

Optimum machining parameters			Power consumption (P) kW		Validation Error (%)
v m/min	f mm/rev	d mm	Experimental	Desirability function approach	6.78
46.20	0.06	0.5	0.0442	0.0412	

5. Conclusions

In this work turning experiments are performed on AISI 6061 Aluminium using a coated tungsten carbide cutting tool. An empirical model is developed using the RSM for power consumption to study the influence of machining parameters on power consumption. The following conclusions are drawn

- Power consumption is most influenced by feed rate subsequently cutting speed and depth of cut.
- The quadratic and interactions terms do not have statistical significance because they have much lower level of contribution and their p-value is also more than the 95% confidence level.

- Contour plots can be used for selection of process parameters to achieve specific power consumption.
- RSM integrated with desirability function approach shows that cutting speed, feed rate and depth of cut has 46.2 m/min, 0.06 mm/rev and 0.5 mm optimal values for minimum power consumption.
- Confirmation experiments validates that the developed empirical model can be used for turning of AISI 6061 Aluminium within 7% error.

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