Investigation of Turning Process Using Field Data Based Approach in Indian Small Scale Industries

Mangesh R. Phate, Chetan K. Mahajan, Mangesh L. Mote, Bharat V. Patil, Harshal G. Patil

Abstract
This paper shows the clear idea about the detailed methodology of mathematical model formulation for the surface roughness, tool temperature, and machine vibration and operator pulse rate during the turning process. It helps to develop an accurate and reliable model for predicting and optimizing the critical process parameters which affects the quality, productivity and the safety of the operator during a step turning process. This paper represents the detailed about the formulation of field data based model to analyze the impact of various machining field parameters on the machining of Aluminum 6063.S.S304, BRASS, EN1A, EN8. In Indian scenario where majority of total machining operation are still executed manually which needs to be focused and develop a mathematical relation which simulate the real input and output data directly from the machining field where the work is actually being executed. The findings indicate that the topic understudy is of great importance as no such approach of field data based mathematical simulation is adopted for the formulation of mathematical model.

Keywords
Step Turning, Field Data Based Model, Sensitivity, Optimization, Buckingham’s Pi Theorem

I. Introduction
Turning is a widely used machining process in manufacturing so selection of cutting parameters to satisfy an economic objective within the constraints of turning operations is a very important task. Traditionally, the selection of cutting conditions for metal cutting is left to the machine operator. Surface roughness, power consumption, material removal rate and productivity has received serious attention for many years. A considerable number of studies have investigated the general effects of the speed, feed, and depth of cut on the turning process. Some researchers studied on the machinability of aluminum-silicon alloys. Liu et. al compared the influence of several factors (cutting speed, feed rate and depth of cut) on cutting force and surface roughness by orthogonal tests in turning Si-Al alloy. The results showed that the surface roughness could be improved by using diamond tool. Recently, in order to obtain reasonable cutting parameters in turning casting aluminum alloy ZL108. Wei, Wang, et al analyzed main influential factors of cutting force using carbide tool YG8. The results indicated the depth of cut had great influence on stability of whole cutting process in rough machining. Armarego et. al (1969) investigated unconstrained machine-parameter optimization using differential calculus.

Brewer et. al (1963) carried out simplified optimum analysis for non-ferrous materials[2]. For cast iron (CI) and steels, they employed for reducing the machining cost to a minimum. A number of monograms were worked out to facilitate the practical determination of the most economic machining conditions. They pointed out that the more difficult-to-machine material have a restricted range of parameters over which machining can be carried out and thus any attempt at optimizing their costs are artificial.

Brewer (1966) suggested the use of Lagrangian multipliers for optimization of the constrained problem of unit cost, with cutting power as the main constraint[2]. Walvekar et. al (1970) discussed the use of geometric programming to selection of machine they optimized cutting speed and feed rate to yield minimum production cost [8]. Petropoulos (1973) investigated. Gopalakrishnan et. al (1991) described the design and development of an analytical tool for the selection of machine parameters in drilling. Geometric programming was used as the basic methodology to determine values for feed rate and cutting speed that minimize the total cost of machining SAE 1045 steel with cemented carbide tools of ISO P-10 grade [5]. Surface finish and machine power were taken as the constraints while optimizing cutting speed and feed rate for a given depth of cut. The chemical composition of the work piece material is as shown in Table 1 and 2.

Table 1: Chemical Composition of Ferrous Materials

<table>
<thead>
<tr>
<th>MTR</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN8</td>
<td>0.4</td>
<td>0.8</td>
<td>0.25</td>
<td>0.05</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EN1A</td>
<td>0.12</td>
<td>0.1</td>
<td>0.1</td>
<td>0.07</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SS304</td>
<td>0.08</td>
<td>0.2</td>
<td>0.75</td>
<td>0.045</td>
<td>0.03</td>
<td>0.18</td>
<td>0.08</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2: Chemical Composition of Nonferrous Materials

<table>
<thead>
<tr>
<th>MTR</th>
<th>Cu</th>
<th>Pb</th>
<th>Ni</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al6063</td>
<td>-</td>
<td>-</td>
<td>0.35</td>
<td>0.1</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Brass</td>
<td>0.95</td>
<td>0.03</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

II. Formulation of Field Data Based Model

A. Need
Data sets contain information and the behaviour of the process variables, often much more than can be learned from just looking at plots of those observed data. Mathematical models based on observed input and output data from real life situation (Machining Process) help us to gain new information and understanding from these data. Thus, it is not possible to plan such activities on the lines of design of experimentation. When one is studying any completely physical phenomenon but the phenomenon is very complex to the extent that it is not possible to formulate a logic based model correlating causes and effects of such a phenomenon, then one is required to go in for the field data based models. Hence the approach of formulating a field data based model is suggested to analysis the machining of ferrous and non-ferrous material on traditional lathe machine.

B. Design of Experimentation
A number of experiments were conducted to study the effects of various machining field parameters on surface roughness of the
work piece. These studies have been undertaken to investigate the effects of various field parameters such as tool, machine, work piece, process and environmental parameters on the surface roughness and other responses. During experimentation, various speed, feed and depth of cut are used for processing the work piece. The output is measured and stored in personal computer for further analysis. In turning operation along with different machining parameters, three shift and seasons is also used during experimentation to analyze the effect of environmental parameters. The approach adopted for formulating generalized experimental model suggested by Hilbert Schenck Jr. [10]

**C. Experimental Setup**

Turning is carried on a lathe that provides the power to turn the work piece at a given rotational speed and feed to the cutting tool at specified rate and depth of cut. Therefore three cutting parameters namely cutting speed, feed and depth of cut need to be determined in a turning operation. The turning operations are accomplished using a cutting tool with high hardness help to sustain the high cutting forces and temperature during machining create a harsh environment for the cutting tool. Surface roughness is another important factor to evaluate cutting performance. The schematic view of the experimental set-up is shown in fig. 1.

![Fig. 1: Experimental Setup](image)

**D. Identifications of Variables**

The term variables are used in a very general sense to apply any physical quantity that undergoes change. If a physical quantity can be changed independent of the other quantities, then it is an independent variable. If a physical quantity changes in response to the variation of one or more number of independent variables, then it is termed as dependent or response variable. If a physical quantity that affects our test is changing in random and uncontrolled manner, then it is called an extraneous variable. The variables affecting the effectiveness of the phenomenon under consideration are single point cutting tool, lathe machine, work piece, process parameters and the environmental parameters. The dependent or the response variables in this case of turning operation is surface roughness. The various dependent and independent variables are as shown in Table 3.

**E. Reduction of Variables by Dimensional Analysis**

1. **Selection of Primary Dimensions**

According to Theories of Engineering experimentation by H. Schenck Jr., “The choice of Primary Dimensions” Most systems require at least three primaries, but the analyst is free to choose any reasonable set he wishes, the only requirement being that his variables must be expressible in his system. There is really nothing basis or fundamental about the primary dimensions. As in this research all the variables are expressed in mass(M), length(L), time(T) hence M, L, and T are choose for the dimensional analysis.

2. **Dimensional Analysis**

The process variables, their symbols and dimensions are given in Table 1. The choice of Primary Dimensions is as shown in Table 3. The best known and the most powerful of these is dimensional analysis. In the past dimensional analysis was primarily used as an experimental tool whereby several experimental variables could be combined to form one. The field of fluid mechanics fluid mechanics and heat transfer were greatly benefited from the application of this tool. Almost every major experiment in this area was planned with its help. Using this principle modern experiments can substantially improve their working techniques and be made shorter requiring less time without loss of control. Delaying the dimensional equation for a phenomenon reduces the number of independent variables in the experiments. The exact mathematical form of this dimensional equation is the targeted model. This is achieved by applying Buckingham’s π theorem (Hibert, 1961). When we apply this theorem to a system involving n independent variables, (n minus number of primary dimensions viz. L, M, T) i.e. (n-3 numbers of π terms are formed.; From equation (2) total number of variables n = 23; All these variables can be expressed in terms of three primary dimensions i.e. mass (M), Length (L) and Time (T), m = 3 According to Buckingham’s theorem Number of Pi terms = n - m = 25 - 03 = 22 dimensionless terms.

\[ f(\pi_1, \pi_2, \pi_3, \ldots, \ldots, \pi_{22}) = 0 \]  

Number of repeating variables are n=m=3; Choosing D, VC and FC are the repeating variables we get following Pi terms as shown in Table 3.

**F. Determination of Plan for Experimentation**

Many discrete extraneous variables like group of men, different machines and instruments, different days of week or seasons of the year can be taken care of by concept of randomized blocks like Latin squares, or Greco-Latin squares, which are among the general family of factorial plans (Logothetisii, 1977). For multifactor experiments two types of plans viz. classical plan or full factorial and factorial plan are available in this experimentation.
5 Weight Raw material W M₁ L⁰ T⁰
6 Initial Diameter of the Work piece Di M₀ L¹ T⁰
7 Length to be turned L M₁ L⁰ T⁰
8 Shank Height H M₁ L⁰ T⁰
9 Tool Length Lt M₀ L¹ T⁰
10 Experience Exp M₀ L⁰ T₁
11 Density of the work piece material DEN M₁ L⁻³ T₀
12 Pulse required Pa M₀ L⁰ T₀
13 Cutting Speed VS M₀ L¹ T⁻¹
14 Feed F M₀ L¹ T⁰
15 Depth of Cut D M₀ L¹ T₀
16 Cutting force FC M₁ L¹ T⁻²

G. Model Formulation

It is necessary to correlate quantitatively various independent and dependent terms involved in this very complex phenomenon. This correlation is nothing but a mathematical model as a design tool for such situation. The Mathematical model for step turning operations is as given below: For Step Turning operation Five independent π terms (π₁, π₂, π₃, π₄, π₅, and π₆) and one dependent π term (πD₁) are decided during experimentation and hence are available for the model formulation. Each dependent π term is the function of the available independent terms, 

\[ \pi_{D1} = K_1 \times \prod_i^r \times \prod_j^s \]  

A probable exact mathematical form for the dimensional equations of the phenomenon could be relationships assumed to be of exponential form [5]. For example, the model representing the behavior of dependent pi term \( \pi_{D1} \) with respect to various independent pi terms can be obtained as under.

\[ \pi_{D1} = K_1 \times \prod_i^r \times \prod_j^s \]  

The values of exponent are a, b, c, d, e, f are established independently at a time, on the basis of data collected through classical experimentation. There are six unknown terms in the equation (5) curve fitting constant K1 and indices a, b, c, d, e, f to get the values of these unknowns we need minimum a set of five set of all unknown dimensionless pi terms.

\[ Z = A + bX + CY \]  

The equation (5) can be brought in the form of equation(6) by taking log on both sides. Model of dependent pi term \( \pi_{D1} \) for surface roughness.

\[ \log \pi_{D1} = \log K_1 + a \log \pi_1 + b \log \pi_2 + c \log \pi_3 + d \log \pi_4 + e \log \pi_5 + f \log \pi_6 \]  

Let, \( Z = \log \pi_{D1} \), \( K = \log K_1 \), \( A = \log \pi_1 \), \( B = \log \pi_2 \), \( C = \log \pi_3 \), \( D = \log \pi_4 \), \( E = \log \pi_5 \), \( F = \log \pi_6 \) Putting the values in equations 4, the same can be written as

\[ Z = nK + aX + bY \]  

Equation (8) is a regression equation of \( Z \) on \( A \), \( B \), \( C \), \( D \) and \( E \) in a dimensional co-ordinate system

\[ \sum Z = nK + aX + bY + cZ + dE + e \sum E \]  

In the above set of equations the values of the multipliers k, a, b, c, d, e and f are substituted to compute the, a, b, c, d and e in the set of equations are calculated. After substituting these values in the equations (9) one will get a set of five equations, which are mutinously to get the values of k, a, b, c, d, e and f. The above equations can be verified in the matrix form and further values of k, a, b, c, d, e and f can be obtained by using matrix analysis. Solving these equations using ‘MATLAB’ is given below.

\[ W = 7 \times 7 \text{ matrix of multipliers of } k, a, b, c, d, e \text{ and } f \]

P1 = 7 x 1 matrix of the terms on L H S and

X1 = 7 x 1 matrix of values of k, a, b, c, d, e and f

After solving we get-the different coefficients

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Table 4: List of Different Dimensional Pi Terms

<table>
<thead>
<tr>
<th>S.N</th>
<th>Ratio</th>
<th>Pi term formulated</th>
<th>Nature of basic physical quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Π₁</td>
<td>An×D /Exp×VC</td>
<td>Operator Parameter</td>
</tr>
<tr>
<td>2</td>
<td>Π₂</td>
<td>(AR×Lt×Lo)/ (R×H)</td>
<td>Cutting Tool Parameter</td>
</tr>
<tr>
<td>3</td>
<td>Π₃</td>
<td>(W×VC×VC×D)/(FC×L×Di)</td>
<td>Workpiece Parameter</td>
</tr>
<tr>
<td>4</td>
<td>Π₄</td>
<td>F/D</td>
<td>Feed</td>
</tr>
<tr>
<td>5</td>
<td>Π₅</td>
<td>P/(VC×FC×SP)</td>
<td>Machine Specification</td>
</tr>
<tr>
<td>6</td>
<td>Π₆</td>
<td>HUM×LUX×D3/(VC×FC×AF)</td>
<td>Atmospheric parameter</td>
</tr>
</tbody>
</table>
Hence the various models formulated model are as follows.

Model 1: Surface Roughness for Ferrous and Non ferrous materials

\[ \Pi_{D_1} = 10^{-1.6909} \times \Pi_1^{0.1926} \times \Pi_2^{0.0506} \times \Pi_3^{3.347} \times \Pi_4^{3.804} \times \Pi_5^{1.712} \times \Pi_6^{0.438} \]

Model 2: Tool temperature for Ferrous and Non ferrous materials

\[ \Pi_{D_2} = 10^{1.3521} \times \Pi_1^{-0.01} \times \Pi_2^{0.0024} \times \Pi_3^{0.368} \times \Pi_4^{-0.0342} \times \Pi_5^{0.6619} \times \Pi_6^{-0.0601} \]

Model 3: Operator Pulse Rate for Ferrous and Non ferrous materials

\[ \Pi_{D_3} = 10^{-2.5886} \times \Pi_1^{-0.2322} \times \Pi_2^{-0.022} \times \Pi_3^{-0.017} \times \Pi_4^{0.0587} \times \Pi_5^{0.0047} \times \Pi_6^{0.0381} \]

III. Result Analysis

A. Model optimization for the Minimum Surface Roughness

The ultimate objective of this work is not merely developing the models but to find out best set of independent variables which will result in minimization of the objective functions. In this case there is one objective functions corresponding to surface roughness models. The objective functions for the surface roughness need to minimize. The models have non-linear form; hence, it is to be converted into a linear form for optimization purpose. This can be achieved by taking the log of both the sides of the model. The linear programming technique is applied which is detailed as below for turning Operation. Taking log of both the sides of the Equation 8, we get, the objective function is taking log of both the sides of the Equation (11), we get, the objective function is

\[ \text{Min } Z = \text{Antilog of } Z \text{ and corresponding to this value of the } \pi \text{ terms needs to be found.} \]

subject to the following constraints

\[ \begin{align*}
1X_1 + 0X_2 + 0X_3 + 0X_4 + 0X_5 + 0X_6 & \leq \text{log}_{10}(\text{Max x1}) \\
1X_1 + 0X_2 + 0X_3 + 0X_4 + 0X_5 + 0X_6 & \geq \text{log}_{10}(\text{Min x1}) \\
0X_1 + 1X_2 + 0X_3 + 0X_4 + 0X_5 + 0X_6 & \leq \text{log}_{10}(\text{Max x2}) \\
0X_1 + 1X_2 + 0X_3 + 0X_4 + 0X_5 + 0X_6 & \geq \text{log}_{10}(\text{Min x2}) \\
0X_1 + 0X_2 + 1X_3 + 0X_4 + 0X_5 + 0X_6 & \leq \text{log}_{10}(\text{Max x3}) \\
0X_1 + 0X_2 + 1X_3 + 0X_4 + 0X_5 + 0X_6 & \geq \text{log}_{10}(\text{Min x3}) \\
0X_1 + 0X_2 + 0X_3 + 1X_4 + 0X_5 + 0X_6 & \leq \text{log}_{10}(\text{Max x4}) \\
0X_1 + 0X_2 + 0X_3 + 1X_4 + 0X_5 + 0X_6 & \geq \text{log}_{10}(\text{Min x4}) \\
0X_1 + 0X_2 + 0X_3 + 0X_4 + 1X_5 + 0X_6 & \leq \text{log}_{10}(\text{Max x5}) \\
0X_1 + 0X_2 + 0X_3 + 0X_4 + 1X_5 + 0X_6 & \geq \text{log}_{10}(\text{Min x5}) \\
0X_1 + 0X_2 + 0X_3 + 0X_4 + 0X_5 + 1X_6 & \leq \text{log}_{10}(\text{Max x6}) \\
0X_1 + 0X_2 + 0X_3 + 0X_4 + 0X_5 + 1X_6 & \geq \text{log}_{10}(\text{Min x6}) \\
\end{align*} \]

On solving the above problem by using MS solver we get optimum value of the objective function and the input variables. Thus \( \Pi_{\text{opt min}} = \text{Antilog Z} \) and corresponding to this value of the \( \Pi_{\text{opt min}} \) the values of the independent \( \pi \) terms are obtained by taking the log of each \( \pi \) term related with surface roughness. Table 5 shows the variation of the various surface roughness due to increase in the values of independent \( \pi \) terms for the turning operation is as shown in Table 5.

B. Validation of the Formulated Generalized Field Data Based Model

The validity of the formulated model can be checked by comparing the actual experimental value of the \( \pi \) term related with surface roughness and its simulated value obtained from the formulated mathematical model. Fig. 3-5. Shows the variation of the actual and simulated result. The error may occur due to error in the measuring instruments.
IV. Discussion

In this study, a generalized field data based model was developed to simulate the step turning process for aluminum 6063, SS304, BRASS, EN1A, EN8. The approach of generalized model formulation model provided an excellent and simple way to analyze the engineering complex process where the impact of field data is dominating the performance. The following primary conclusions appear to be justified from the above model.

Model 1: Surface Roughness Model
- The absolute index of $\pi_4$ is highest viz. 0.3804. Thus in $\pi_4$ the terms related to the feed which is the most influencing factors in this phenomenon. The value of this index is positive indicating $\pi D_1$ is directly varying with respect to $\pi_4$.
- The absolute index of $\pi_2$ is lowest viz. -0.0506, then $\pi_2$ related to cutting too, parameter is the least influencing pi term in the model. The value of the index is negative indicating $\pi D_1$ is inversely varying with respect to $\pi_2$.
- The sequence of influence of the other independent pi terms present in the model is $\pi_4, \pi_1, \pi_6, \pi_3, \pi_5, \pi_2$ having absolute indices(0.3804, 0.1926, 0.0438, -0.347, -0.1732, -0.0506) respectively. The index of $\pi 2$ is negative indicating that $\pi D_1$ inversely proportional with respect to $\pi 2$.
- The curve fitting constant in the model is 0.02037511. This value represents the effect of clearances and other factors which affect the phenomena.

Sensitivity analysis of step cutting operation indicates single point cutting tool and the cutting process parameters are most sensitive and work piece parameter, lathe machine specification as well as machining environmental parameters are least sensitive for model $\Pi D_1$ and hence needs strong improvement.

Model 2: Cutting Tool temperature Model
- The absolute index of $\pi_5$ is highest viz. 0.0619. Thus in $\pi_5$ the terms related to the machine specification which is the least influencing factors in this phenomenon. The value of this index is positive indicating $\Pi D_2$ is inversely varying with respect to $\pi 5$.
- The absolute index of $\pi_6$ is lowest viz. -0.0501, then $\pi_6$ related to atmospheric data is the most influencing pi term in the model. The value of the index is negative indicating $\Pi D_2$ is directly varying with respect to $\pi 6$. 

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Fig. 2: Graph for Experimental and Computed Value of $\pi$ Term Related with the Surface Roughness

Fig. 3: Graph for Experimental and Computed Value of $\pi$ Term Related with the Cutting Tool Temperature

Fig. 4: Graph for Experimental and Computed Value of $\pi$ Term Related with the Machine Vibration

Fig. 5: Graph for Experimental and Computed Value of $\pi$ Term Related with the Operator Pulse Rate
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References

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