2.1 INTRODUCTION

A cutting tool may fail during the process due to many working conditions such as softening, brittle fracture, due to sudden mechanical load changes/shocks, gradual wear in working piece, etc. The stresses develop due to the resistance of the work material at the prevailing temperature and strain rate cause rounding off the cutting edge due to inadequate strength of the cutting edge. The area of contact at the flank expands forcing the effluent too material past the flank surface. However, if the ratio of the hardness of the tool and chip material is modified for prevalent cutting temperature and strain-rate, such failures are not expected and “form stability” will be achieved [29].

Failures by brittle fracture are to excessive pressure and load or such shocks are present in intermittent cuttings, quick freezing of the cutting action, cutting under chatter condition, etc. however, such brittle fractures are avoidable by proper selection of cutting conditions (feed, depth of cut, etc.) and increasing the wedge angle of the tool or by strengthening the cutting edge with a land, etc. Under usual conditions of cutting, when the “form stability” of the cutting edge has been achieved or failure by brittle fracture is prevented, cutting tools still
continue to fail by a process of wear which is due to interaction between the chip and the tool or between the work piece and the tool.

After the cutting has progressed for some time, wear takes place in two different regions on the cutting tool. The wear will appear on the flank of the tool below the cutting edge forming a wear land extending approximately parallel to the cutting edge. The wear will also appear on the tool face forming a characteristic cavity known as ‘crater’ which begins at a certain distance from the cutting edge. Economy in metal is associated with an increase in production rates, with acceptable dimensional accuracy and finish. The useful life of a cutting tool is limited by wear. Hence, productivity is directly affected by the wear of cutting tools. The principal concern of machine ability research is to investigate the basic mechanism of wear by which tool life is governed [30].

2.1.1 Causes of Tool Wear

There are two interrelated causes for tool wear are mechanical abrasion and thermal erosion. Although these two actions take place simultaneously, the role of each varies for various cutting conditions. Mechanical wear is dominant when low cutting speeds are used or when the work piece possesses high machinability. Thermal wear prevails when high cutting speeds are used with work pieces having low mach
inability. Thermal wear is due to diffusion, oxidation, and the fact that the mechanical properties of the tool change as a result of the high temperature generated during the cutting operation. The face of the cutting tool is subjected to friction caused by the fast relative motion of the generated chips onto its surface. Similarly, the flanks are also subjected to friction as a result of rubbing by the work piece. Although the tool is harder than the work piece, friction and wear takes place but it cannot even distributed over the face of the tool. The cutting tool wear which can be described as a tool loss at weight or mass of the sliding pairs may be classified according to the probable mechanism of wear [31, 32]:

1. Mechanical process like abrasion and adhesion.
2. Thermo-chemical process like diffusion.
3. Electrochemical process like localized galvanic action.

When the rubbing surfaces are not in an active chemical environment and deterioration by electrical interaction of electricity absent, the mechanical wear process contributes mainly to the total wear volume, particularly at low sliding or rubbing speed and takes place in two predominant ways:

1. Abrasion due to ploughing the softer matrix by hard constituents such as segregated carbides and inclusions.
2. Adhesion and formation of metallic bonds formed over the rubbing surfaces subjected to pressure with subsequent ruptures these bonds followed by transfer of elementary particles.

Wear is localized in the vicinity of the cutting edge and results in the formation of a crater. There are different kinds of tool wear depending on mechanism of tool wear:

1. Flank wear.
2. Wear of the face that comes in contact with the removed chip.
3. Wear of the cutting edge itself.
4. Wear of the nose.
5. Wear and formation of a crater.
6. Cracks in the cutting edges occurring during interrupted machining operations such as millings [33].

2.1.2 Mechanisms of Tool Wear

Evidence indicates that wear is a complex phenomenon and is influenced by many factors. The causes of wear neither behave in the same manner, nor they always affect wear to the same degree under similar cutting conditions. The causes of wear are not fully understood. In recent years, great strides have been made by various researches. Even though there is some disagreement regarding the true mechanisms by which wear
actually takes place, most investigators feel that there are at least five basic causes of wear as follows:

1. Abrasive action of hard particles contained in the work material.
2. Plastic deformation of the cutting edge.
3. Chemical decomposition of the cutting tool contact surfaces.
4. Diffusion between work and tool material.

The relative effects of these causes are a function of cutting velocity or cutting temperatures. Investigations have also been made on other possible causes such as oxidation and electrochemical reactions in the tool work contact zone.

The most important factor influencing tool wear is cutting temperature. Of the four basic causes of wear, temperature has considerable effect in all but, one cutting temperatures is important for two basic reasons: (1) most tool materials shown rapid loss of strength hardness, and resistance to abrasion above some critical temperature, and (2) the rate of diffusion between work and tool materials rises very rapidly as temperature increases past the critical [34].

2.2 TOOL FAILURE

The cutting tool failures when it is no longer capable of producing parts within required specifications. The point of failure, together with the amount of wear that determines this failure, is a function of the
machining objective. Surface quality, dimensional stability, cutting forces, cutting horsepower, and production rates may alone, or in combination, be used as criteria for tool failure. The various elements of wear of a cutting tool is shown in Fig. 2.1a&b&c.

Tool failure is associated with some of breakdown of the cutting edges. This breakdown takes place gradually over a period of time. In the absence of rigidity, or because of improper tool geometry that gives inadequate support to the cutting edge, the tool can fail by mechanical fracture of chipping under the load of the cutting forces [35]. This is not truly a wear phenomenon for it can be eliminated or at least minimized by proper design and application.

As a result of direct contact with the work material, there are three major regions on the tool where wear can take place: 1) Face, 2) Flank and 3) Nose, as for Fig.2.1:b&c.

![Fig.2.1 (a) Various Elements of Wear A Cutting Tool](image-url)


Fig. 2.1(b) Various Elements of Wear A Cutting Tool Failures

2.2.1 Face Wear

The face of the tool is the surface over which the chip passes during its formation. Wear takes the form of a cavity or crater, which has its origin not along the cutting edge but at some distance away from it and within the chip contact area. As wear progresses with time, the crater gets wider, longer and deeper and approaches the edges of the tool.

This form of wear is usually associated with ductile materials which give rise to continuous chips. If crater wear is allowed to proceed too far, the cutting edge becomes weak as it thins out, and breaks down suddenly. Usually, there is some preliminary breakthrough of the crater at the nose and at the preliminary breaks, serve as focal points for the development of craters along the flank. In general, crater wear develops faster than flank wear on ductile materials and is the limiting factor in determination of tool failure.
2.2.2 Flank Wear

Although crater wear is the most prominent in the machining of ductile materials, flank wear is always present regardless of work and tool material, or even of cutting conditions. The flank is the clearance face of the cutting tool, along which the major cutting edge is located. It is the portion of the tool that is in contact with the work at the chip separations point and that resists the feeding forces. Because of the clearance, initial contact is made along the cutting edge. Flank wear begins at the cutting edge and develops into a wider and wider flat of increasing contact area called a wear land.

Materials do not form continuous chips promote little if any crater wear, and flank wear becomes the dominant factor in tool failure. In the case of most form tools and certain milling cutters, the wear land is in direct contact with the finished surface, and usually becomes the basis for failure even on ductile materials, particularly surface finish specifications are the controlling factors in the process. Quite often, flank wear is accompanied by a rounding of the cutting edge, particularly in the machining of abrasive materials. This results in large increase of cutting and feeding forces which, if carried too far, could lead to tool fracture.
2.2.3 Nose Wear

Nose wear is similar to and if often considered a part of flank wear. There are times when it should be considered separately. Nose wear sometimes proceeds at a faster rate than flank wear, particularly when one is working on rather abrasive materials and using small nose radii. In finish turning operations, for example, excessive wear will affect finished part dimensions as well as surface roughness. If sharp corners are specified on the part drawing, the rounding or flattening of the nose can cause out of tolerance conditions long before flank wear itself becomes a factor.

2.3 TOOL LIFE

Tool life is defined as the length of actual machining time beginning at the moment when a just-ground tool is used and ending at the moment when the machining operation is stopped because of the poor performance of that tool. Different criteria can be used to judge the moment at which the machining operation should be stopped. It is common to consider the tool life as over when the flank wear reaches a certain amount (measured as the length along the surface generated due to abrasion starting from the tip). This maximum permissible flank wear is taken as 0.062 inch (1.58 mm) in the case of high-speed steel tools and 0.03 inch (0.76 mm) for carbide tools. The tool life is affected by several variables, the important ones being cutting speed, feed, and the coolants used. The effect of these variables can be determined
experimentally and then represented graphically for practical use. By Frederick W. Taylor found the relationship between tool life and cutting speed is exponential [29]. It can, therefore, be plotted on a logarithmic scale so that it takes the form of a straight.

The types and mechanisms of tool failure have been previously described. It was shown that excessive cutting speeds cause a rapid failure of the cutting edge thus, the tool can be declared to have a short life. Other criteria sometimes used to evaluate tool life are:

I. Change of quality of the machined surface.

II. Change in the magnitude of the cutting force resulting in changes in machine and work piece deflections causing work piece dimensions to change.

III. Change in the cutting temperature and,

III. Cost, including labor costs, tool costs, tool changing time (cost), etc.

The selection of the correct cutting speed has an important bearing on the economics of all metal cutting operations. Fortunately, the correct cutting speed can be estimated with reasonable accuracy from tool-life graphs or from the Taylor’s tool life relationship, provided that necessary data is obtainable. The logarithm of tool life in minutes is plotted against the logarithm of cutting speed in meters per minute as shown in Fig. 2.2 (a). The resulting of the tool life is very nearly a straight line in most
instances. For practical purposes, it can be considered a straight line.

Taylor’s tool life relation is expressed by the following equation.

\[ VT^n = C \]  \hspace{1cm} (2.1)

Where \( V \) = cutting speed, meter per minute.

\( T \) = tool life, minutes.

\( C \) = a constant equal to the interest of the straight line and the ordinate.

\( N \) = slope of log \( V \) vs log \( T \).

The main tool life in terms of time series analysis is a model that should reproduce the past behavior of the series, exploiting its autocorrelation structure. Since a pure time series model does not include explanatory variables, these forecasts of future observation are simply extrapolation of the observed series at the end of the sample. For single variable studying, univariate time series model is used. But if two or more variables are available, there is a possibility of dynamic interactions among them. In this case, multivariate time series models can be constructed to take into account the relations among variables in automation industrial processes of the manufacturing of metal cutting process by flank wear [30].

**2.4 ECONOMICS OF METAL CUTTING OPERATIONS**

Our goal now is to find out the operating conditions (mainly the cutting speed) that maximize the metal-removal rate or the tool life. These two
variables are in opposition to each other; a higher metal-removal rate results in a shorter tool life. Therefore, some trade-off or balance must be made in order to achieve either minimum machining cost per piece or maximum production rate, whichever is necessitated by the production requirements.

Fig. 2.2(a) indicates how to construct the relationship between the cutting speed and the total cost per piece for a simple turning operation. The total cost is composed of four components: machining cost, idle-time (nonproductive) cost, tool cost, and tool-change cost. An increase in cutting speed obviously results in a reduction in machining time and, therefore, lowers machining cost. This is accompanied by a reduction in tool life, thus increasing tool and tool-change costs. As can be seen in Fig.2.2 (a), the curve of the cost per piece versus the cutting speed has a

Fig.2.2 Various elements of tool wear relationship in between product time per piece and cutting tool speed
minimum that corresponds to the optimum cutting speed for the minimum cost per piece. The relationship between the production time per piece and the cutting speed can be constructed in the same manner, as shown in Fig.2.2 (b). There is also a minimum for this curve that corresponds to the optimum cutting speed for the maximum productivity (minimum time per piece). Usually, this value is higher than the maximum economy speed given in Fig.2.2 (a). Obviously, a cutting speed between these two limits (and depending upon the goals to be achieved) is recommended.

Both these depend on the choice of cutting parameters, e.g., cutting speed, feed, and depth of cut. Generally, a component goes through various operations and an exact economic analysis is extremely complicated. But, at the same time, in mass scale production, often one operation is performed in one special machine; thus, we shall an attempt to carry out a preliminary analysis, considering single operations. Such analysis provides us with some basic information on the important economic aspects of the machining operations. To avoid complications, we shall restrict our analysis to the simple turning operation of cylindrical bars [29].

In fact, from the economic point of view, the best situation is when profit is maximum. A large rate of production may result in a better
return, and therefore it is also useful to investigate the conditions leading to the highest possible rate of production.

The maximum production rate can be achieved if the total time required per piece is reduced to a minimum. For this, we shall search for the optimum value of on-line metal cutting process by tool wear with the monitoring and controlling of different controller strategies, like PI Controller, Neuro-PID, and Fuzzy Logic Controllers. Based on experimental modeling and evaluation by using these techniques, controller parameters of metal cutting process $K_P$, $K_I$, $K_D$ can be varied. By varying the controller parameters of flank wear $K_P$, $K_I$, $K_D$ using above controller techniques the non-linear flank wear can be modified into linear model [36, 37].

The mathematical model of flank wear has been developed, by using the theory developed in this chapter. A detailed description of this is given in the next section.

2.5 MODELLING OF THE NON-LINEAR FLANK WEAR MODEL

The details about the experimentation to obtain data used for modeling of Non-linear flank wear model in metal cutting process are presented. The objective of modeling is to obtain the simplest mathematical description that is adequate to predict the response of the physical
system for all anticipated inputs. Modeling techniques for prediction, classification and pattern recognitions are discussed in detailed.

For the sake of recognition or classification of metal cutting process of flank wear, the effects of changes in the manipulating factors have been described without regard to their influence upon such criteria as tool wear and tool life [38]. Yet, there is no tool materials know that can completely resist contact and rubbing at high temperatures and high pressures without some changes from its original contours over a period of time.

It becomes necessary, to analyze the effect of the manipulating factors not only upon the metal cutting process itself, but also upon the performance of the cutting tool, which may itself affect the metal cutting process [30].

2.5.1 CONDUCTING TESTS ON METAL CUTTING PROCESS OF FLANK WEAR MODEL

Flank wear sensing should be one of the primary objectives in order to produce the required end products in an automated industry so that a new tool may be introduced at the instant and with the existing tool has worn out, thus presenting any damage occurring in the machine or deformation of surface finish.
Plate 2.1 Flank wear measurement using optical microscope

Plate 2.2 CNC Lathe used for the case study
A reliable and inexpensive tool monitoring system for cutting process would contributed to the effective utilization of machine tools, cutting tool and work pieces. However, tool wear monitoring based on current signal has unacceptably high cost or performance ratios and are effective only under limited range of cutting conditions on line flank wear monitoring and tool replacement at proper time are important techniques to be developed to realize a fully automated manufacturing system as it is necessary to present damage of cutting tools, machine tool and work pieces. The spindle speed may change according to advanced control strategies. The reference a wear estimation strategy that operates under varying cutting conditions of parameters are speed \( v \), the feed rate \( f \) and dept of cut \( d \) as well as on its wear \( w \).

In order to establish the model of the current signal as a function of cutting parameters and tool wear, the effects of cutting parameters and tool wear based on current signal are first examined. The metal cutting process is shown in Plate 2.1; the experimental set-up is illustrated in Plate 2.2.

The essence of the method is to establish a simple model relating the measured current value and the flank wear state under different cutting conditions. Experiments are carried out in a Computer Numerical Control (CNC) lathe using K10 cemented carbide tool. The work piece material used for the experiment is LM25 AL(Aluminum) or 10% SiCb (Silicon Carbide) particulate rein force composite material prepared
through stir casting. The cutting conditions used for experimentation are listed in table 2.1.

*Table 2.1 Experiment conditions for metal cutting process*

<table>
<thead>
<tr>
<th>Cutting conditions</th>
<th>Cutting Speed(^{(v)}) Feed rate(^{(f)}) Depth of Cut(^{(d)})</th>
<th>250, 740 and 1150 rpm and 1.07 m/rev 0.5, 0.8 and 1.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Work piece</strong></td>
<td>Al+10% of Sicb</td>
<td>Particulate reinforced Composite material</td>
</tr>
<tr>
<td><strong>Cutting Tool</strong></td>
<td>K10 Cement</td>
<td>Carbide</td>
</tr>
</tbody>
</table>

Cutting tests are performed on a CNC-lathe machine driven by Permanent Magnet Direct Current (PMDC) motor. A PMDC motor is

*Table 2.2 Experiment Cutting conditions and corresponding outputs (training cases)*

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Cutting Speed(^{(rpm)})</th>
<th>Feed rate (mm/rev)</th>
<th>Depth of Cut (mm)</th>
<th>Spindle motor current (mA)</th>
<th>Flank wear (mm)</th>
<th>Surface Roughness [Ra](^{(\mu m)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>740</td>
<td>0.1</td>
<td>0.8</td>
<td>892</td>
<td>0.3</td>
<td>1.10</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>1.1</td>
<td>0.8</td>
<td>956</td>
<td>0.3</td>
<td>2.88</td>
</tr>
<tr>
<td>3</td>
<td>740</td>
<td>1.1</td>
<td>0.5</td>
<td>968</td>
<td>0.3</td>
<td>2.20</td>
</tr>
<tr>
<td>4</td>
<td>1150</td>
<td>1.1</td>
<td>0.8</td>
<td>1094</td>
<td>0.3</td>
<td>1.97</td>
</tr>
<tr>
<td>5</td>
<td>740</td>
<td>1.1</td>
<td>1.0</td>
<td>1126</td>
<td>0.3</td>
<td>2.20</td>
</tr>
<tr>
<td>6</td>
<td>740</td>
<td>0.1</td>
<td>0.8</td>
<td>934</td>
<td>0.4</td>
<td>1.51</td>
</tr>
<tr>
<td>7</td>
<td>250</td>
<td>1.1</td>
<td>0.5</td>
<td>982</td>
<td>0.4</td>
<td>3.96</td>
</tr>
</tbody>
</table>
similar to an ordinary DC shunt motor except that its field is provided by permanent magnet instead of salient pole wound field structure.

**Table 2.3 Experiment cutting conditions and corresponding outputs (test samples)**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Cutting Speed(rpm)</th>
<th>Feed rate (mm/rev)</th>
<th>Depth of Cut (mm)</th>
<th>Spindle motor current(mA)</th>
<th>Flank wear (mm)</th>
<th>Surface Roughness(Ra) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1150</td>
<td>0.1</td>
<td>1.0</td>
<td>952</td>
<td>0.3</td>
<td>0.9861</td>
</tr>
<tr>
<td>2</td>
<td>740</td>
<td>1.1</td>
<td>0.5</td>
<td>968</td>
<td>0.3</td>
<td>2.201</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>1.1</td>
<td>0.8</td>
<td>954</td>
<td>0.3</td>
<td>2.8878</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>-----</td>
<td>----</td>
<td>----</td>
<td>-----</td>
<td>----</td>
<td>-----</td>
</tr>
<tr>
<td>4</td>
<td>740</td>
<td>0.1</td>
<td>0.5</td>
<td>948</td>
<td>0.4</td>
<td>1.5108</td>
</tr>
<tr>
<td>5</td>
<td>1150</td>
<td>1.1</td>
<td>0.8</td>
<td>1173</td>
<td>0.4</td>
<td>2.7058</td>
</tr>
<tr>
<td>6</td>
<td>740</td>
<td>1.1</td>
<td>0.5</td>
<td>1027</td>
<td>0.5</td>
<td>3.8616</td>
</tr>
<tr>
<td>7</td>
<td>1150</td>
<td>1.1</td>
<td>0.8</td>
<td>1173</td>
<td>0.4</td>
<td>2.7058</td>
</tr>
<tr>
<td>8</td>
<td>740</td>
<td>1.1</td>
<td>0.5</td>
<td>968</td>
<td>0.3</td>
<td>2.2013</td>
</tr>
<tr>
<td>9</td>
<td>250</td>
<td>1.1</td>
<td>0.8</td>
<td>954</td>
<td>0.3</td>
<td>2.8878</td>
</tr>
<tr>
<td>10</td>
<td>740</td>
<td>1.1</td>
<td>0.5</td>
<td>1027</td>
<td>0.5</td>
<td>3.8616</td>
</tr>
<tr>
<td>11</td>
<td>1150</td>
<td>1.1</td>
<td>1.0</td>
<td>1306</td>
<td>0.7</td>
<td>5.5726</td>
</tr>
<tr>
<td>12</td>
<td>250</td>
<td>0.1</td>
<td>0.5</td>
<td>1092</td>
<td>0.8</td>
<td>4.2478</td>
</tr>
<tr>
<td>13</td>
<td>1150</td>
<td>0.1</td>
<td>1.0</td>
<td>1290</td>
<td>0.9</td>
<td>3.3238</td>
</tr>
<tr>
<td>14</td>
<td>250</td>
<td>1.1</td>
<td>0.8</td>
<td>1116</td>
<td>0.9</td>
<td>9.6693</td>
</tr>
<tr>
<td>15</td>
<td>740</td>
<td>0.1</td>
<td>0.5</td>
<td>948</td>
<td>0.4</td>
<td>1.5108</td>
</tr>
</tbody>
</table>

In such motors torque is produced by interaction between the axial current carrying conductors and the magnetic flux produced by the permanent magnets. The DC motor current of the lathe is measured. A personnel computer is interfaced with the cutting operation is performed automatically. Plate 2.1 shows an optical microscope which is interfaced with the computer in order to view the flank wear state [38].

The experiments are conducted for various sets of cutting conditions that includes cutting speed feed rate and depth of cut. For each set of cutting conditions, machine is done starting with a fresh tool
inserted continuing until the tool wear out. The surface roughness is then measured using Talysurf-3 surface tester for the different cutting conditions at various time intervals and the centre line average values (Ra) are estimated.

A total of 56 tool wear cutting tests are conducted under different cutting conditions 20 sample data are randomly selected and used as learning sampled as show in table 2.2. The remaining 15 sample are used as the test samples in the classification/pattern recognition phase as modeling of flank wear as illustrated in table 2.3.

2.5.1.1 Modeling

In general, the term modeling refers to the description of the system by a set of mathematical equations. A mathematical model of industrial processes and control of system operation are based on physical principles or empirical relation. However, for many of the industrial process it is difficult to obtain mathematical model because of their complex behavior, typical characteristics and operating conditions.

For dynamic state model of metal cutting process, input, output and state variables have to be selected from the experimental data which is shown in the table 2.3. The inputs to a turning process are the feed (f), the cutting speed (vc) and the depth of cut (d). In this model the cutting speed and depth of cut are assumed to be constant, as it is typically the
case in any one segment of a turning operation. Thus, the input variables are selected to be the feed only for purposes of parameter and state estimation. The output is selected to be the cutting force ($F_c$), which is directly measurable during the process. The state variables, as a modeling requirement for state estimation equations, have to represent the wear components. Therefore, they are selected to be two of the most frequently present types of wear [38], namely flank wear ($w_f$) basis on the sum of components are the Abrasive action of hard particles contained in the work material($W_{f1}$) and Diffusion between work and tool material($W_{f2}$).

As the second step in the construction of the model, the state and output equations have to be determined from flank wear components. For this, the relationships reported in the literature for single point turning operations are reviewed and those which define the simplest and clearest relationship between the model variables (input, output, and state variables) are selected for modeling the non-linear flank wear mechanism [40].

2.6 THE NON-LINEAR FLANK WEAR MODEL

Tool wear sensing should be one of the primary objectives in order to produce the required end products in an automated industry. The direct measurement of tool wear in real time, during cutting operation is an impossible task. There existed considered research efforts affected in modeling the correlation between the measurable variables such as
cutting force, temperature and tool wear. The results show that the cutting force provides significant information about the state of machining process and tool wear.

There are four important types of wear to be considered. They are crater wear, major flank wear, minor flank wear and nose wear. All of them are important but the amount of flank wear if often used in determining the tool life.

The block diagram of surface roughness model for control of flank wear and tool wear monitoring shown in Fig.2.3. The surface roughness model is a regression model based on experimental data obtained from table 2.2. The tool wear model is a dynamic model which is derived from dynamic nature of tool wear based on the flank wear by koren et.al.

![Fig.2.3 Block diagram of model formation for metal cutting process](image)

The developed dynamic mathematical model is used to relate the wear to the input parameters for a turning operation. The input parameters were
established based on the design of experiment technique. The model is used to predict the tool wear. These tool wear values were compared with the experimental flank wear values. The non-linear flank wear model contains many of the important variables such as cutting force \( F_c \), the flank wear \( W_f \), cutting temperature \( \theta_f \), the feed \( f \), the depth of cut \( a \) and the cutting speed \( V_c \).

The present work includes development of mathematical model and comparing it with experimental results. The index of wear and the hardness of tool influencing the flank wear were used as input parameters to develop the mathematical model. The developed mathematical model is used to relate the wear to the input parameters for a turning operation. The input parameters were established based on the design of experiment technique. These tool wear values were compared with the experimental flank wear values.

The flank wear model contains many of the important variables such as cutting force, the flank wear, cutting temperature, the feed, the depth of cut and the cutting speed. In this model flank wear is separated into two components: one caused by abrasion \( W_{f1} \) and the other by diffusion \( W_{f2} \)\[39,40\]. These two components are used as state variables in terms of all important experimental variables. The input to the process is cutting speed \( V_c \). The experimental observation data in table 2.2 and
table 2.3 are used to model the flank wear mechanism. Accordingly, state model is described as:

\[
W_{f1} = \frac{-V_c}{I_o} W_{f1} + \frac{V_c}{I_o} K_F \frac{F_c}{fa} \cos(\alpha r) \tag{2.1}
\]

\[
W_{f2} = K_D \sqrt{V_c} \exp \left[ -\frac{A_c}{273 + \theta_f} \right] \tag{2.2}
\]

where the tools wear \( W_f \) the sum of two components of the flank wear \( W_{f1} \) and \( W_{f2} \).

**2.6.1 Output Variable**

The output variable (\( F_c \)) of our dynamic state model is selected to be the cutting force, since, force measurement is currently the most reliable and accurate sensing method available in metal cutting process.

It is generally assumed that the components of cutting force are linearly related to flank wear. Unlike flank wear can have a sharpening effect and can cause the force to decrease as a result of growing crater wear.

The opposing effects of flank wear on the cutting force is one of the major draw backs in wear sensing through force measurement, since at high cutting speed. Perhaps the most general force relationship is presented by Koren and Lenz [41,42].

\[
F_c = F_o + aC_w W_f \tag{2.3}
\]

\[
F_o = (K_4 f^m (1 - K_s \alpha r) - K_6 - K_7 V_c) a \tag{2.4}
\]
In the equation (2.1) \( \alpha_r \) is an effective rake angle; \( C_w, l_0, K_F, K_D, K_4, K_5, K_6, K_7, n_1, \) and \( A_e \) are the model parameters which are defined as constant parameters depending on the cutting conditions and tool work piece combination as shown in table 2.3. \( F_0 \) is the vertical component of the initial cutting force for the sharp tool.

\( \Theta_f \) is the tool-work piece temperature on the flank wear side of the tool. An alternative way to obtain the tool-work temperature is to calculate it using an empirical relation [39, 43].

\[
\theta_f = K_F V_f X_f a_f F_c \tag{2.5}
\]

Another relation is given by

\[
\theta_f = K_9 V_c^{n_2} f_{n_3} + K_{10} W_f^{n_4} \tag{2.6}
\]

<table>
<thead>
<tr>
<th>Table 2.4 Parameter values used in the simulation of model</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_0 )</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>( K_5 )</td>
</tr>
<tr>
<td>0.57</td>
</tr>
<tr>
<td>( n_1 )</td>
</tr>
<tr>
<td>0.76</td>
</tr>
</tbody>
</table>

where \( K_7, X, Y, Z, K_9, K_{10}, n_2, n_3 \) and \( n_4 \) are the model parameters, depending on the cutting conditions and tool work piece combination as shown in the table 2.3. The model in state variable form can be represented as follows:
\[
x_1 = aK_2C_w(x_1 + x_2 + x_3) \quad (2.7)
\]
\[
x_2 = \frac{1}{\tau}\left(K_oF_o - x_2\right) \quad (2.8)
\]
\[
x_3 = aK_1C_w(x_1 + x_2 + x_3) \quad (2.9)
\]
\[
F_C = F_o + aC_wW_f \quad (2.10)
\]

where \( x_1, x_2 \) and \( x_3 \) are the state variables.

\[
W_{f1} = x_2 + x_3 \quad (2.11)
\]
\[
W_{f2} = x_1 \quad (2.12)
\]
\[
W_f = W_{f1} + W_{f2} = x_1 + x_2 + x_3 \quad (2.13)
\]

Where \( K_o, K_1, K_2, C_w \) and \( \tau \) are model parameters.

This model can be compactly written in matrix action or form as follows:

\[
x = A_0x + B_0u \quad (2.14)
\]
\[
y_0 = C_0x + Du \quad (2.15)
\]

Where

\[
A_0 = \begin{bmatrix}
ak_2c_w & ak_2c_w & ak_2c_w \\
0 & -\frac{1}{\tau} & 0 \\
aka_c_w & ak_1c_w & ak_1c_w
\end{bmatrix}
\]
\[
B_0 = \begin{bmatrix}
k_2 \\
k_0 \\
0
\end{bmatrix} \quad ; \quad C_0 = [ac_w \quad ac_w \quad ac_w] \quad ; \quad D = [1]
\]

and \( x \) is the state vector, \( \tau = [x_1 \quad x_2 \quad x_3] \)
In this case study we replace the flank wear model equation (2.5) with equations (2.1-2.4) and (2.6) for simulation purpose. As in other works we will assume here that the parameters of equation (2.6) are known, this model discussed above, equations (2.1-2.4) and (2.6) have been evaluated using integration to get the conversion from wear-rate to wear. It is important to note that the simulated model of the process is non-linear equations (2.1)-(2.4) and (2.6), and also notice that the simulation results shows the non-linear flank wear response as shown Fig.2.4.

![Graph of Flank Wear Response](image)

**Fig. 2.4 Open Loop Response of Flank Wear [Surface Roughness]**

The mechanically activated mechanism is represented by a first order lag with a time constant, which varies inversely with the cutting speed. The total wear $W_f$ at any time is the sum of the wear [43] due to the thermally activated mechanism $W_{f1}$ and the wear due to the
mechanically activated mechanism, \( W_{f2} \) using the parameter values as given in table 2.3 and found to agree with experimental results of table 2.1 & 2.2 are reported used as the basis for roughness control and tool wear monitoring, the open loop response of surface roughness is shown in Fig. 2.4[16].

Notice that this model response as shown in Fig.2.4 is nonlinear, equations 2.7-2.9 gives equations for flank wear in state variables. A drawback for practical utilization of the nonlinear flank wear model,(2.1-2.4), is the difficulty to obtain a linear system with its parameters \( C_w, I_o, K_F, K_D, K_4, K_5, K_6, K_7, n_1, \) and \( A_e. \)

The flank wear model response of nonlinear model has been linearized by using advanced control strategies of conventional controller and non-conventional controller techniques. In this chapter based on tool wear mechanism experimental data, flank wear model is described and the relevant equations are obtained. However, the model obtained is non-linear. The non-linear model can be linearized by using tuning of PID controller techniques. Hence, there is a need to develop new methods for transforming non-linear system into linear system, the details of which are explained in following chapters.