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Simulation and performance evaluation of metal cutting processes from NC programs

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The University of Arizona, 1993
SIMULATION AND PERFORMANCE EVALUATION OF METAL CUTTING PROCESSES FROM NC PROGRAMS

by

Srinivas Polisetty

A Thesis Submitted to the Faculty of the DEPARTMENT OF SYSTEMS AND INDUSTRIAL ENGINEERING In Partial Fulfillment of the Requirements For the Degree of MASTER OF SCIENCE WITH A MAJOR IN SYSTEMS ENGINEERING In the Graduate College THE UNIVERSITY OF ARIZONA 1993
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Jan 13, 1993.

Date
To my parents
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ABSTRACT

Existing NC verification tools concentrate on graphical display of tool path and collision detection only. The objective of this work is to demonstrate that information regarding the nature of machining being performed can be extracted from NC code, work and tool material properties, and initial geometric profile of workpiece. Based on this information, values of performance measures (such as cutting force, tool wear, cutting temperatures, chip formation and surface finish) can be estimated using theoretical or empirical models. A software simulation tool is developed to demonstrate this. The software tool runs under X-Windows on a Sun workstation. It generates the following output: graphical display of tool path, cutting forces, tool-chip interface temperature, flank wear of cutting tool, surface finish generated and nature of chip formation. At every stage of simulation, the current profile of workpiece resulting from each machining operation is computed, by finding regions of intersection of previous workpiece profile and current tool path. In its present version, this software tool is capable of simulating performance measures for turning operations only. However, it can perform graphical display of 3-D toolpath.
# NOTATION

- $a$: constant exponent in the relation between hardness and temperature of tool in wear model
- $B, B_i$: constants used in the equation for wear rate for tool flank
- $c_p$: probability that a sizable wear particle of the harder material will be formed
- $c_t$: tool hardness
- $c_w$: penetration hardness of the workpiece
- $C$: strain rate constant for workpiece material
- $C_0$: concentration of diffusing species at the tool-work interface
- $dt$: increment in time
- $D$: diffusion coefficient
- $e_a$: area of welded asperity joints
- $e_c$: concentration of diffusing species
- $e_g$: gas constant
- $e_l$: clearance angle of tool
- $e_n$: number of welded asperity joints
- $e_r$: thermal number used in orthogonal machining theory
- $e_t$: thermal diffusivity of workpiece
- $e_v$: volume of asperity joint torn off
- $e_w$: weight percentage of diffusing species in the tool material
- $e_y$: height of welded joint torn off in shear
\( \Delta e_y \)  
height of tool material removed in time \( \Delta t \)

\( F \)  
frictional force at tool-chip interface

\( F_C \)  
force in the direction of cutting velocity

\( F_f \)  
friction force on tool flank

\( F_N \)  
normal force on shear plane \( AB \) (Fig 3.1.)

\( F_S \)  
shear force on shear plane \( AB \)

\( F_t \)  
thrust force on flank

\( F_T \)  
force normal to the direction of cutting velocity

\( G \)  
specific weight of the workpiece material

\( h \)  
tool-chip contact length

\( J \)  
flux of diffusing atoms (atoms per unit time)

\( k \)  
shear flow stress

\( k_{AB} \)  
shear flow stress along shear plane \( AB \)

\( k_{chip} \)  
shear flow stress along tool-chip interface

\( K \)  
thermal conductivity of workpiece

\( l \)  
length of shear plane \( AB \), \( l = t_1 / \sin \phi \)

\( L \)  
wear land on the tool flank

\( m \)  
atomic weight of the diffusing species

\( n \)  
strain hardening index of workpiece

\( N \)  
normal force at tool-chip interface

\( p \)  
ydrostatic stress on shear plane

\( P_m \)  
apparent contact pressure on tool flank

\( Q \)  
activation energy for diffusion

\( R \)  
resultant cutting force

\( s_1 \)  
distance measured along slipline

\( s_2 \)  
distance measured normal to slipline
\( S \) specific heat of workpiece

\( t_1 \) undeformed chip thickness

\( t_2 \) chip thickness

\( T_{AB} \) temperature along shear plane \( AB \)

\( T_C \) average temperature in chip

\( \Delta T_C \) average temperature rise in chip

\( T_{int} \) average temperature along tool-chip interface

\( T_K \) initial temperature of flank in Kelvin

\( T_{mod} \) velocity modified temperature

\( \Delta T_M \) maximum temperature rise in chip

\( T_0 \) initial temperature of flank in Celsius

\( \Delta T_{SZ} \) temperature rise in primary shear zone

\( T_w \) initial work temperature

\( U \) cutting (work) velocity

\( V \) chip velocity, \( V = \frac{U \sin \phi}{\cos(\phi - \alpha)} \)

\( dV_{ol} \) change in volume of tool material due to flank wear

\( V_S \) shear velocity, \( V_S = \frac{U \cos \alpha}{\cos(\phi - \alpha)} \)

\( w \) width of cut measured along cutting edge

\( \alpha \) tool rake angle

\( \beta \) proportion of heat conducted into work

\( \gamma \) shear strain

\( \gamma_{AB} \) shear strain at shear plane \( AB \)

\( \dot{\gamma} \) shear strain rate

\( \dot{\gamma}_{AB} \) shear strain rate along shear plane \( AB \)

\( \dot{\gamma}_{int} \) shear strain rate along tool-chip interface
\( \delta \) ratio of thickness of tool-chip interface plastic zone to chip thickness

\( \epsilon \) uniaxial (effective) strain

\( \epsilon_{AB} \) effective strain along shear plane \( AB \)

\( \dot{\epsilon} \) uniaxial (effective) strain rate

\( \dot{\epsilon}_0 \) constant in equation for \( T_{mod} \)

\( \eta \) temperature factor

\( \theta \) inclination of \( R \) to shear plane \( AB \)

\( \lambda \) angle between \( R \) and \( N \)

\( \mu \) coefficient of friction on tool flank

\( \nu \) constant in equation for \( T_{mod} \)

\( \rho \) density

\( \rho_t \) density of tool material

\( \rho_w \) density of work material

\( \sigma \) uniaxial (effective) flow stress

\( \sigma_N \) average normal stress at tool-chip interface

\( \sigma'_N \) normal stress at tool-chip interface from boundary condition at \( B \) determined from stress distribution along shear plane \( AB \)

\( \sigma_1 \) value of \( \sigma \) at \( \epsilon = 1 \)

\( \tau_{int} \) resolved shear stress at tool-chip interface

\( \phi \) shear angle

\( \psi \) temperature factor
CHAPTER 1

Introduction

Integrated Computer Aided Design and Computer Aided Manufacturing have become a necessary part of any manufacturing enterprise. The benefits of integration of operations can be further improved by extending its scope into other related areas such as engineering, sales, marketing and distribution. The meaning of integration, which is popularly known as Computer Integrated Manufacture (CIM) in this context is that, all areas of business access a common information database. Some of the benefits of CIM are listed below.

• **Increased market share:** The ability to economically produce small volumes allows the manufacturer to cater to different segments of the market.

• **Reduced engineering costs:** Quick access to accurate information and ease of change of design reduce design time and manpower costs.

• **Lower production costs:** Better design and engineering reduce production costs. Effective utilization of information can reduce inventory level and improve overall productivity.
However, the key benefit of CAD/CAM can be attributed to reduction in product lead time. Present day manufacturing industry is confronted with the problem of shrinking product life and increased product complexity, leading to longer lead times. In order to maintain competitiveness, manufacturers should be able to design and develop a new product and standardize its manufacturing process in the shortest possible time period.

The following steps are usually involved between design and production of a component. In this work, a component is assumed to be made of some metal and a product is made from such components. Manufacturing operations on a component are meant to be machining operations such as turning, milling, drilling, etc. Typically, once the design phase of a component is completed, the process planner takes over. The process planner decides machine tools on which the component is to be manufactured, the kind of cutting tools to be used, the sequence of operations to be performed, and also decides the process parameters (such as cutting speeds and feeds). Once a process plan is established, the part programmer develops a Numerical Control (NC) program for the specific process plan. Then the NC program is down-loaded on to the machine tool and a prototype is machined to check the part program for logical errors. As one can see, this process is time consuming and error prone. Moreover, a machine tool has to be freed of its scheduled work in order to machine the prototype. Fortunately, several software tools are now available to help the
process planner and part programmer to rapidly develop an error-free and optimum NC program to machine a given component. Some of the existing tools are:

1. The General Electric data system [1]. This system uses empirical machinability models to determine optimum machining conditions for minimum cost and maximum production.

2. FAST (Feed And Speed Technology) [1]. This system is used to simplify the process of selecting proper cutting tools for machining operations and of determining the proper feeds and speeds for those tools. FAST also provides estimates of operation times.

3. EXAPT [1]. It is similar to the well-known APT programming language with some enhancements. In addition to regular APT statements, EXAPT contains APT-like statements for describing workpiece initial and finished geometry and technological operation data such as work material code, machine tool specifications and surface finish requirements. Other fixed inputs to EXAPT are tool data, material data and machine tool data. With these inputs EXAPT processor selects operation sequences, cutting tools and collision-free tool motions. It can also determine optimum machining conditions if the economic, empirical and theoretical metal-cutting conditions are input to the system.

Considerable research has been conducted in the areas of computer aided process planning and NC verification. Jagdale [2] developed an automated process planning
system for rotational parts using artificial intelligence methodologies. It generates a process plan from a feature based description of the part and other technological inputs. Vittal et al. [3] developed a computer-aided process planning system for rotational parts in an FMS environment. The system, known as CAPP-RP, is capable of generating process plans for operations such as turning, drilling, facing, boring, etc. It is capable of generating alternative process plans whenever one of the machine tools ceases to be available. Pande et al. [4] developed a computer assisted process planner called PC-CAPP for prismatic components. This software has the following modules 1) Component feature representation. 2) Machine, tooling and process parameter selection. 3) Setup planning. 4) Production time calculation. 5) Report generation. Gouda et al. [5] published a complete survey of available computer aided process planning systems. It includes variant, semigenenerative, generative and expert process planning systems. A total of 128 CAPP systems were surveyed by them and tabulated to provide the computer hardware, part type, required input data, the process, the output and the developer.

The work presented here focusses on NC program verification. Hereafter NC program verification is referred to as NC verification. NC verification is a major step in reducing lead time and prototype development cost. Currently, several software tools are available to graphically animate cutting tool motion generated by an NC program. With help from these tools one can visually check cutter movement for possible part gouging, collision of workpiece and tool holder, out of tolerance areas, etc.
Details of available NC verification tools and current research in this area are given in the literature survey section. Further improvements in the process of NC verification will enable us to predict from the NC program other machining performance indicators such as cutting force, tool wear, cutting temperatures, chip formation and surface finish. A survey of literature indicates that very little work has been done in this area. In subsequent chapters, we will present a software tool that takes NC program as input and generates graphical display of tool path along with dynamic simulation and display of machining performance indicators.
CHAPTER 2

Literature survey

Extensive literature survey indicates that very little work has been done in integrating models of various performance measure indicators into a single usable simulation tool for machining. However, a lot of effort has been devoted to graphical NC verification. Commercial CAD/CAM packages such as SmartCam (of Point Control Software) and MasterCam (of CNC Software) provide several tools for rapid NC code generation. They also have features for visual verification of the tool path generated by means of animating tool path over superimposed work piece. Other recent publications of interest in this area are listed below. Zhu [6] reported work on formulas to detect interference points between tool and workpiece, which could be used in NC verification. Chen et al. [7] developed a tool to simulate NC tool path directly from IGES-based CAD data. Oliver and Goodman [8] discuss techniques for comparing profile generated by NC program with a model of the desired part. A graphical output depicts the desired part as shaded surface with out of tolerance areas highlighted. All of the above tools focused attention on only one aspect of NC verification, namely NC tool path display. Surprisingly, there is little published material on simulation of machining performance indicators based on NC code.
Though models for cutting force, tool wear, etc. exist, they have been developed in isolation by researchers in those respective areas. These models have been used for adaptive control of machining processes and for optimization of machining parameters such as feed, speed and depth of cut. Stephenson and Wu [9, 10] have developed computer models for the mechanics of three dimensional cutting processes. They have used a numerical modeling method for predicting chip thickness, chip-tool contact length, and the qualitative effect of varying the depth of cut. Danai and Ulsoy [11] presented a state model for tool wear designed for an adaptive observer which was used for on-line tool wear sensing in turning based on force measurement. Crawford et al. [12] developed a state space model of metal cutting on a lathe to monitor tool flank and crater wear. As evident, these models were developed for a specific purpose. After careful consideration of several such models, we chose some of them to be used in the simulation that has been developed. Wherever possible, theoretical models were chosen over empirical ones. Another consideration was, all the parameters that drive the model should either be available from the NC program to be simulated or tool and work material data. Detailed references and description of particular models that have been used are presented in appropriate sections.
CHAPTER 3

Models of machining performance indicators

In order to predict cutting force, temperature, tool wear, etc., we need either theoretical or empirical models of such performance indicators. We could not find satisfactory theoretical models to predict chip formation and surface finish. Hence empirical models are used for those performance measures. The advantage of using theoretical models over empirical ones is that relationships expressed in them are more fundamental, and hence rely on limited data about workpiece and tool. Thus, the same model can be used for different materials if data for such material is available. The following sections contain details about the various models that were used for this simulation tool.

3.1 Cutting force and temperature model

Cutting forces and temperatures are two of the most important machining performance indicators. Other indicators (such as power consumption and tool life) can easily be determined once forces and temperature are known. Also, they can be used in optimizing machining parameters. Therefore, we have chosen to simulate cutting
forces and tool chip interface temperature from information available in NC programs and additional work material and tool data.

Considerable work has been done in the area of determining cutting force and cutting temperature. Some of the widely used models are listed below. Most of these methods can be classified into two main groups [13]. One group estimates the lower bound values for force and the other produces upper bound values. Lower bound values are computed based on the theory of maximum dissipation of energy and the system tends to reach state of minimum energy. Slight changes in material composition may not result in all the energy being used for deformation and hence might produce higher values of stress. In the upper bound solution, it is assumed that an element deforms in such a way as to offer maximum resistance. So, if stresses are determined from assumed deformation, the estimate will be greater than or equal to that actually occurring. Some of the better known models that fall into these categories are Ernst and Merchant's upper bound solution [13], Loladze's angle relation [13], Lee and Shaffer's lower bound solution [13], Oxley's thin shear zone model [13].

Many of these models depend on the availability of suitable experimental data. Applicability of such models is limited by range of parameters, under which such data has been gathered. Work done by Oxley et al. [14] acknowledges this limitation and hence they propose a more fundamental machining theory, based upon cutting conditions and knowledge of flow stress and thermal properties of the workpiece material. Most of the above mentioned models predict only the cutting forces and
chip geometry. But in addition to predicting forces and temperature, the model developed by Oxley et al. shows how they can be used to predict built-up edge range, tool wear rates and those cutting conditions which cause plastic deformation of the cutting edge. Moreover, they extended their theory to consider effects of oblique machining [14], end cutting edge [15], tool nose radius and prior cold working of work piece [16] on cutting forces and temperature.

Therefore, we have chosen the model developed by Oxley et al. for our simulation purposes. For the sake of simplicity and reduced computational complexity, only orthogonal machining theory is considered and other extensions to it are avoided. A brief description of orthogonal machining theory as presented by Oxley [15] is given next and then the numerical procedure used to determine cutting forces and tool chip interface temperature based on this theory is described.

**Orthogonal machining theory:**

In orthogonal machining, a layer of material is removed by a single, straight cutting edge, which is normal to the cutting velocity. This process approximates to one of plane strain, if the thickness of the layer removed is small compared with its width. According to this theory, the plane AB (Fig 3.1.) and tool-chip interface are both assumed to be directions of maximum shear stress and maximum shear strain rate. A boundary layer of thickness $\delta t_2$ exists in the chip adjacent to the tool face. The velocity changes linearly from zero at the tool surface to chip velocity $V$. The stresses along AB and tool chip interface are analyzed in terms of shear plane angle $\phi$, work
Figure 3.1: Orthogonal chip formation model

material properties and cutting conditions. The value for $\phi$ is determined as a point at which shear stress $\tau_{int}$ calculated from resultant force across AB, equals shear flow stress $k_{chip}$ in the chip material at the interface. The main equations of the theory are as follows.

(a) For plane AB:

\[
\tan \theta = 1 + 2 \left( \frac{\pi}{4} - \phi \right) - Cn \tag{3.1}
\]

\[
\theta = \phi + \lambda - \alpha \tag{3.2}
\]

\[
\dot{\gamma}_{AB} = \frac{CV_S}{l} \tag{3.3}
\]

\[
\gamma_{AB} = \frac{\cos \alpha}{2 \sin \phi \cos(\phi - \alpha)} \tag{3.4}
\]

\[
\Delta T_{SZ} = \frac{1 - \beta}{\rho S t_1 w} \frac{F_S \cos \alpha}{\cos(\phi - \alpha)} \tag{3.5}
\]
\[ T_{AB} = T_W + \eta \Delta T_{SZ} \]  
(3.6)

\[ \sigma'_N = k_{AB} \left( 1 + \frac{\pi}{2} - 2\alpha - 2Cn \right) \]  
(3.7)

\[ x = \begin{cases} 
0.5 - 0.35 \log(e_r \tan \phi), & 0.04 \leq e_r \tan \phi \leq 10.0 \\
0.3 - 0.15 \log(e_r \tan \phi), & e_r \tan \phi > 10.0 
\end{cases} \]  
(3.8)

\[ e_r = \frac{\rho SUt_1}{K} \]  
(3.9)

(b) For the tool-chip interface:

\[ \dot{\gamma}_{int} = \frac{V}{\delta t_2} \]  
(3.10)

\[ \Delta T_C = \frac{F \sin \phi}{\rho S t_1 w \cos(\phi - \alpha)} \]  
(3.11)

\[ \log \left( \frac{\Delta T_M}{\Delta T_C} \right) = 0.06 - 0.195\delta \left( \frac{e_r t_2}{h} \right)^{1/2} + 0.5 \log \left( \frac{e_r t_2}{h} \right) \]  
(3.12)

\[ T_{int} = T_W + \Delta T_{SZ} + \psi \Delta T_M \]  
(3.13)

\[ h = \frac{t_1 \sin \theta}{\cos \lambda \sin \phi} \times \left[ 1 + \frac{Cn}{3 \{1 + 2(\pi/4 - \phi) - Cn\}} \right] \]  
(3.14)

\[ \sigma_N = \frac{N}{h w} \]  
(3.15)

With the knowledge of thermal properties of work piece, its flow stress properties, and above equations, the value for \( \phi \) can be determined and also the values of forces, temperature, etc. for given values of \( \alpha, u, t_1, w \) and \( T_w \). The strain rate constant \( C \) is found by considering the stress boundary conditions at cutting edge (B in Fig 3.1.), and \( \delta \) selected so as to minimize the shear flow stress at the tool-chip interface, and hence to minimize the rate of both frictional work \( FV \) and total work \( F_c U \).
Work material flow stress properties:

In turning operations, typical values of strain and temperature [16] would be in the range of 1 to 2 and 150°C to 250°C respectively in primary shear zone and 3 to much higher values and 800°C to 1200°C in the tool-chip interface. Limited flow stress data are available at these extreme conditions. Recently, Oyane et al. [17] conducted some tests and proposed a linear logarithmic stress strain relation

$$\sigma = \sigma_1 \epsilon^n$$  \hspace{1cm} (3.16)

where $\sigma$ and $\epsilon$ are uniaxial flow stress and strain. The stress $\sigma_1$ (value of $\sigma$ at $\epsilon = 1$) and strain hardening index $n$ are material constants which define the stress-strain curve for given values of strain rate and temperature. To relate the flow stress to strain rate and temperatures, a velocity modified temperature is computed and $\sigma_1$ and $n$ are expressed as functions of this temperature. The velocity modified temperature is defined by

$$T_{\text{mod}} = T (1 - \nu \log \frac{\dot{\epsilon}}{\epsilon_0})$$  \hspace{1cm} (3.17)

where $T$ is in Kelvin, $\dot{\epsilon}$ is the uniaxial strain rate and $\nu$ and $\epsilon_0$ are constants for a given work material. Typical curves for $\sigma_1$ and $n$ for 0.2% carbon steel and 0.38% carbon steel are shown in Fig 3.2. For the purpose of computation, we express these curves as mathematical equations for different ranges of $T_{\text{mod}}$. The specific heat and thermal conductivity of the material are temperature-dependent and hence appropriate empirical relations (shown below) have to be used for the given work material. The constants $s_1,s_2,k_1 \text{ and } k_2$ are material dependent.
Figure 3.2: $\sigma_1$ and $n$ curves for work materials.

\[ S = s_1 + s_2(T) \]  
(3.18)

\[ K = k_1 + k_2(T) \]  
(3.19)

The algorithm used to determine cutting forces and tool-chip interface temperature is shown in Fig 3.3.
Given: cutting conditions \( o, U, t_1, w, T_W \) and material properties

Assign values for \( \delta, \delta_1, ..., \delta_{final} \)

\( \delta = \delta_1 \)

Assume initial value of \( C \) (say \( C = 3 \))

Assume \( \phi \) (say \( \phi = 5° \))

Calculate \( l = t_1 / \sin \phi, V_S \) from Fig 3.1, stackrel: \( c_{AB} \) from eqn 3.3 \( c_{AB} = c_{AB} / \sqrt{3}, c_{AB} = c_{AB} / \sqrt{3} \)

Assume \( T_{AB} = T_W \)

\( T_{AB} = \text{new} T_{AB} \)

Compare new \( T_{AB} \) and old \( T_{AB} \)

\( \Delta T_{SG} \) from eqn 3.5 and forces \( R = F_S / \cos \phi, F = F_S / \sin \phi, N = F_S / \cos \phi \)

Calculate for the interface \( T_2 \) from Fig 3.1, \( V \) from eqn 3.14, \( \tau_{INT} = F / h, \tau_{INT} \) from eqn 3.10, \( \tau_{INT} = \tau_{INT} / \sqrt{3} \)

Calculate mean chip temperature \( T_C = T_W + \Delta T_{SG} \)

\( T_C = \text{new} T_C \)

Compare new \( T_C \) and old \( T_C \)

\( \phi = \phi + 0.1° \)

\( \phi = 45° \)

Plot \( \tau_{INT} \) and \( c_{CHIP} \) versus \( \phi \) and select solution point \( \phi \) where \( \tau_{INT} = c_{CHIP} \)

\( \phi = 45° \)

\( \phi = 45° \)

\( \phi = 45° \)

Estimate new \( C \)

\( \delta = \delta_{min} \)

\( \delta = \delta_{final} \)

\( \delta = \delta_{final} \)

Plot \( F_C \) versus \( \delta \) and determine \( \delta = \delta_{min} \) for minimum \( F_C \)

Print out \( \phi, \) forces etc. for minimum work

Figure 3.3: Summary of method of orthogonal machining calculations
3.2 Tool wear model

As part of NC verification and simulation, we would like to estimate tool wear to predict tool life. The following observations are made after careful study of several models of cutting tool wear. Most of the literature has focussed on flank wear of tool more than crater wear. Flank wear has more direct influence on the quality of product. Onset of crater wear results in a change in the mechanics of the cutting process, i.e. change in effective rake angle and tool-chip contact length. Flank wear, on the other hand results in change in mechanics of the process, increased tendency for chatter and change in dimensions of the product. Therefore, we decided to consider flank wear of cutting tool for this simulation.

Several people have presented their work on flank wear. Some of the notable ones are that of Bhattacharya and Ham [18], Rubenstein [19], Koren [20], Koren and Lenz [21], Bhattacharya and Ghosh [22], and Kannatey-Asibu [23]. The model presented by Kannatey-Asibu is used in this work, since it considers both adhesive and diffusion wear together. The model also suggests ways of estimating tool life based on adhesion and diffusion wear rate. According to this model, the flank wear rate is given by

\[
\frac{dL}{dt} = B_2 U (T_o + BL^{0.25})^\alpha + B_3 \sqrt{U} e^{-(\frac{q}{2T_C + BL^{0.25}})} L^{-1/2}
\]

(3.20)

where

\[
B_2 = c_p \left(\frac{\cot \epsilon_l - \tan \alpha}{c_w c_l T_o} \right) \frac{e_n}{Lw} \left(\frac{e_n}{Lw}\right)^{1/2}
\]
In this model, the rate of flank wear is expressed by considering effects of adhesion and diffusion on wear process. The relationship is based on the mechanics of wear process, friction and diffusion. Also, the regenerative effects of wear, temperature and friction force are considered. For the purpose of simulation, the equations presented in this model are used and rate of flank wear in terms of change of wear land is calculated at small increments of time. Then length of wear land is updated by adding this incremental change to previous land length. The adhesion wear rate and diffusion wear rate are also monitored. As suggested by Kannatey-Asibu, the beginning of the end of tool life is indicated when diffusion rate exceeds adhesion rate. Constraints regarding use of this model are that one has to refer to different sources for data regarding work material and tool material required in this model. Selection of values for some of the variables used in this model are explained below.

- $e_n/L_w$: The number of asperities per unit area. According to Bowden and Tabor [24], under loads similar to those incurred in metal cutting, the average size of an asperity is of the order of 0.01 mm. In this model it is assumed that asperities are spaced at a distance equal to their diameter. Hence the number of asperities per square millimeter is $10^4$.
• *e_y*: The height of asperities were also reported to be $5 \times 10^{-3}$ mm for the unloaded surface [24]. It has been assumed in this model that the height torn off is 20 percent of the unloaded height. Hence,

\[ e_y = 10^{-3} \text{ mm} \]

• $\mu P_m = \frac{F_c}{F_T} \cdot \frac{F_T}{L_w} = \frac{F_c}{L_w}$

• $B_o = c_{i,y}$

Assumptions: Cutting process is assumed to be orthogonal

### 3.3 Chip formation model

For the purposes of unmanned machining, it is important to be able to determine the type of chip generated for a given set of machining parameters. A continuous chip may be unsuitable for unmanned machining because, if not disposed promptly, it might get entangled with the rotating parts and also affect surface finish generated when the chip is in contact with machined surface. In that case, the NC program may have to be halted at regular intervals to enable chip disposal. Therefore, we have chosen to simulate chip control in turning processes. Our literature survey indicated lack of theoretical models for determining chip nature. Therefore, an empirical solution suggested by Nakamura, Christopher and Wuebbling [25] is used in this simulation. In their work, experimental turning tests were conducted on several materials to determine the effects of side cutting edge angle, cutting speed, workpiece material and chip-breaker shape on chip control. Regression analysis techniques were applied to
determine acceptable and unacceptable regions of chip control based on feed rate and depth of cut. From their study, the following conclusions were made.

1. Side cutting edge angle of the tool and the cutting speed have a small effect on chip breakage phenomena.

2. Workpiece material and chip-breaker shape have significant effects on the chip-breakage phenomena. The effect of these variables can be expressed by the equation $F = K_c R$ where $F$ is the lower limiting feed, $R$ is chip flow radius which is calculated from tool geometry and $K_c$ is a constant related to workpiece material.

3. Limiting feed and depth of cut are interrelated.

Chips are classified based on physical appearance. Continuous chips are classified as unacceptable whereas discontinuous ones are classified as acceptable. Figure 3.4 shows different classifications of chips and different chip breaker geometries. Chip classifications numbered 1, 2 and 3 are considered unacceptable. One of the parameters influencing chip control is chip flow radius. It can be calculated from chip-breaker configuration as shown below.

1. Groove-type chip-breaker,

$$R = \frac{H}{2} + \frac{W^2}{8H}$$

where $R$ is chip flow radius, $H$ is depth of groove and $W$ is width of groove.
Taken from the paper by Wuebbling et al. [25].

Figure 3.4: Chip classification and chip breaker types.
2. Obstruction-type chip breaker,

\[ R = W \cot(\theta/2) \]

where \( W \) is width of rake face and \( \theta \) is the angle between rake face and obstacle face.

3. Land-angle type chip breaker. It is regarded as identical to the obstruction type, which has the width of rake face \( W + L/2 \), where \( W \) is the rake-face width of the land-angle-type, and \( L \) is its land length.

The constant \( K \) is dependent on workpiece material. Values of \( K \) for some common materials are given in table 3.3. Having known values of \( K \) and \( R \), the lower limiting feed can be calculated by the equation \( F = K_c R \) where \( F \) is given in millimeters per revolution, \( R \) is given in millimeters. Based on the above equation, it can be said that any feed lower than lower limiting feed would result in unacceptable chip (i.e., a continuous one).

### 3.4 Surface finish model

The surface finish obtained is another important performance indicator of a machining process. The selection of machining parameters for finish machining of a part is determined by its surface finish requirements. Therefore, a suitable surface finish prediction model will enable us to check if the finish machining operations satisfy the prescribed surface finish requirements.
Several studies have been made in modeling surface finish. Some of them are by Bhattacharya and Gonzalez [26], Lambert and Taraman [27], Lambert and Sundaram [28], Mehta and Mital [29]. Most of the models have focussed on a narrow variety of engineering materials, namely carbon and alloy steels. Mehta and Mital consider other alloys such as cast aluminum, cast iron and inconel. Hence their model is chosen for this simulation tool.

Though geometric surface finish in single point turning is affected by cutting speed, feed rate and nose radius, the actual finish from turning is influenced by factors such as workpiece hardness, built-up edge, depth of cut, side and end cutting edge angles of the tool. Mehta and Mital used the randomized complete block factorial design with blocking on metals for collecting surface finish data. Using this data, a general purpose surface finish prediction model was developed. According to this model the surface finish $SF$ (in microns) is given by

<table>
<thead>
<tr>
<th>Workpiece material</th>
<th>Constant $K_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 4140, HB 179</td>
<td>0.065</td>
</tr>
<tr>
<td>AISI 4140, HB 341</td>
<td>0.093</td>
</tr>
<tr>
<td>AISI 4140, HB 415</td>
<td>0.099</td>
</tr>
<tr>
<td>AISI 8620</td>
<td>0.057</td>
</tr>
<tr>
<td>INCONEL 718</td>
<td>0.049</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>0.085</td>
</tr>
</tbody>
</table>

Table 3.1: Constant $K_c$ in chip control model for various materials

Taken from the paper by Wuebbling et al. [25].
\[ SF = \begin{cases} 
-98.53 - 114.28(F) + 0.27(M \times R) + 0.006(S \times R) - 12.22(R \times F) \\
-0.0012(M \times S \times R) + 0.0016(M \times S \times R \times F) - 2.26 \log(S) \\
+111.25 \exp(F) + 0.004 \exp(M) - 125.89(1/S) + 0.78(1/R) \\
-0.072(1/F) + 0.97(1/M) 
\end{cases} \]

where

\( S \) = cutting speed (m/min); \( F \) = feed rate (mm/rev);
\( R \) = tool nose radius (mm); \( M \) = material code.

The values of \( M \) for various materials are as below.

- Cast iron = 1
- Medium carbon leaded steel 10L45 = 2
- Medium carbon alloy steel 4130 = 3
- Inconel alloy 718 = 4
- Aluminum alloy 390 = 5

The surface finish values were based on the arithmetic average values \( R_a \) obtained from the tests.

To summarize, we have chosen the following models for each of the performance indicators.

- **Cutting forces:** Orthogonal machining theory as proposed by Oxley et al. [14].
• **Cutting temperature:** Orthogonal machining theory as proposed by Oxley et al. [14].

• **Tool wear:** Transport diffusion theory as proposed by Kannatey-Asibu. [23].

• **Surface finish:** General purpose surface finish models developed by Mehta et al. [29].

• **Chip nature:** Chip control theory based on feed rate and depth of cut as proposed by Nakamura et al. [25].
CHAPTER 4

Development of simulation tool

In this chapter, details regarding the goals, implementation issues, assumptions and limitations of the NC verification and simulation tool are presented. Detailed instructions for using the software, and preparation of input files are available in the user manual [30]. Logical flow diagrams and explanations of algorithms used are available in the technical manual [31].

4.1 The environment

This software tool runs on a Sun workstation under X-window system. The X-Window system is a device independent, network transparent, graphics windowing system for bit mapped display hardware. Programs written using X-Windows are portable and can be run on a computer network of different hardware configurations. This is achieved by use of the client-server model which is now popular. The graphics display station runs a program which controls its screen. It accepts service requests from other programs and displays that information in a window on the screen. Hence it is called a server. The requesting programs are called clients. Clients can reside on same machine as the server or on any other host which can make a network connection
to the server. Fig 4.1 shows a typical installation of clients and server in a network. The Benefits of using X-Window system for graphical output are:

- The computational part of the program can be done on one computer and its graphical display can be sent to a specialized graphics terminal running X-server.

- Several computers connected in a network can share use of one expensive graphics display terminal.

- Programs written in X can be ported with minimal modifications to different hardware.

- X-Window system is gaining acceptance as the industry standard for graphics display.

- Several tools based on X are available for implementing better user interface and advanced graphics routines.

4.2 Simulation objectives

The primary objective of this software tool is to demonstrate that the information necessary to compute performance indicators such as force, temperature, etc. can be extracted from the NC program, initial workpiece profile information, tool and work material properties. In order to determine performance measures in real time, we need models to simulate those values from a minimal set of data with the least
Figure 4.1: Schematic of a client server network
computational effort. A detailed literature search was conducted to find such models of machining performance indicators as discussed in chapter 3. Wherever possible, mathematical models were preferred over empirical ones, because of their validity over wider range of operating conditions. Another important goal of this simulation tool was modular design. The simulation tool is not tightly bound to any one particular model of performance indicator. This way when a better model is available at a later stage, the program can use it with very little modification. The new model can be incorporated into this software by first rewriting the function that computes performance indicator based on this model and secondly to alter data load routines in order to load any other additional material or tool data that is needed by the new model.

4.3 Implementation of software

The software is implemented in 'C' programming language. The graphics display section is implemented with the use of Xlib routines.

4.3.1 Design specifications

This software is capable of generating graphical display of tool path for two and three axis machining. It can also simulate and generate graphical display of performance measures such as cutting force, temperature, tool wear, chip formation and
surface finish for turning, boring, parting and grooving operations. The required inputs are:

1. NC program to be simulated.

2. Workpiece material properties.

3. Cutting tool geometry and properties.

4. Workpiece profile geometry data.

The outputs of the software are

1. Graphical display of top view of profile and tool path during turning and top, front and side view of tool path during three axis machining.

2. Dynamic graphical plots of cutting forces, tool chip interface temperature, diffusion and adhesion wear rates of tool flank, length of wear land and surface finish generated.

In addition, numerical display of following is generated:

UNIT          Unit of measurement used in NC program. Possible values are Inches or millimeters.

INTRPOL       Interpolation mode of current NC block (Linear, Point to point, Clockwise circular, Counter clockwise circular).
SPEED(mode) Measurement of spindle speed. (revolutions per minute(rpm) or Constant surface speed(CSS) ).

FEED(mode) Mode of measurement of feed. Units per revolution(UPR) or units per minute(UPM).

TNRC Tool nose radius compensation. (Off, Right, Left)

SPEED(value) current value of cutting speed.

FEED(value) current value of feed.

COOLANT Indicates whether coolant is ON or OFF.

SPINDLE Direction of rotation of spindle. (CW or CCW)

Depth Depth of cut in meters.

Width Width of cut in meters.

Cutvel Cutting velocity in meters per second.

Force FC Cutting force (in Newtons) in the direction of cutting.

Force FT Cutting force (in Newtons) normal to direction of cutting.

Wear AD Flank wear rate due to adhesion in millimeters per second.

Wear DF Flank wear rate due to diffusion in millimeters per second.

Chip Nature of chip being produced. Good: discontinuous, Bad: continuous.

Surface F Surface finish generated in microns.
Temp TC  Tool chip interface temperature in Celcius.

Wear Land  Length of flank wear land in millimeters.

End tool life  YES: Beginning of end of tool life because diffusion wear rate has exceeded adhesion rate. NO: Otherwise.

Cutting edge  Status of cutting edge. OK or DEFORMED.

Builtup edge  Presence of built-up edge. YES or NO.

NC BLOCK  Current NC block that is being simulated.

ACTION  Explanation of M codes.

The simulated values of performance indicators are also sent to stderr for every unique combination of depth of cut, width of cut, cutting velocity for a given material and cutting tool combination. The software tool is also capable of predicting the end of tool life, the onset of built-up edge and plastic deformation of cutting edge. The input NC program can either be in inch or metric mode but not both. Feed can be given in units per revolution or units per minute mode, cutting speed in revolutions per minute or constant surface speed mode. The turret is assumed to have a maximum of 15 slots for tools. Figure 4.2 shows a snapshot of a typical simulation run.

4.3.2 Input data preparation

Before the given NC program can be simulated, data files for workpiece material properties, cutting tool material properties, cutting tool geometry and other machine
Figure 4.2: Snapshot of a simulation run
setup information such as various tools in turret and various tool fonts have to be prepared.

The following are all the input data files required by this software.

- File that contains standard NC program in M and G codes.
- Data file describing style and font of the tool path for each of the cutting tools.
- Data file that lists the tool loaded into each of the turret slot.
- File that contains data about machining environment variables and constants such as apparent contact pressure on tool flank, initial temperature of workpiece and cutting tool.
- File that contains data about workpiece material properties such as density, hardness, thermal diffusivity and thermal conductivity.
- File that contains data about cutting tool material properties such as rake angle, hardness, diffusion coefficient, atomic weight of diffusing species, chip breaker type, nose radius, etc.
- File that contains data about coefficient of friction between various combinations of tool and workpiece materials.
- File that contains data about flow stress properties of the work material.
- File that contains data about strain hardening properties of the work material.
• File that contains data about start ordinate of Y in the graph and the scaling amounts.

• File that contains data about initial and outer profile of workpiece.

In order to determine depth of cut, it is necessary to keep track of current profile of workpiece. The profile is described by means of straight line equations, which are mappings from Z to X described by $X = f(Z)$ ∀ $Z_2 > Z < Z_1$. Figure 4.3 represents the physical configuration and coordinate system that has been assumed for this software tool. Figures 4.4 and 4.5 show example profiles and corresponding data files. The circular portion of the profile is approximated by a set of straight line equations. The number of straight line segments chosen depends on accuracy required. The format of profile data file is as below.

<table>
<thead>
<tr>
<th>ID</th>
<th>type</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>z1</td>
<td>float</td>
<td>Z coordinate of starting point of profile segment</td>
</tr>
<tr>
<td>z2</td>
<td>float</td>
<td>Z coordinate of end point of profile segment</td>
</tr>
<tr>
<td>c1</td>
<td>float</td>
<td>slope of straight line</td>
</tr>
<tr>
<td>c2</td>
<td>float</td>
<td>X coordinate when Z is zero</td>
</tr>
</tbody>
</table>
4.3.3 General program flow

This section presents general outline of logic flow used in this simulation tool. Figures 4.6 thru 4.9 are flowcharts depicting general program flow. Before the start of actual simulation, the program prompts for several inputs. They are as follows.

1. File name containing the NC program to be simulated.

2. File name containing the initial outer profile geometry of workpiece. This is used to determine width of cut during turning, grooving and parting.

3. File name containing the initial inner profile geometry of workpiece. This is used to determine width of cut during boring and drilling operations.

4. Workpiece material code. This code is decided during preparation of workpiece material data file.

Figure 4.3: Coordinate system used and turret location.
Figure 4.4: Example outer profile.

Data file for above outer profile

\[
\begin{align*}
0 & \ -4 & \ -0.5 & \ 2 \\
-4 & \ -5 & \ 0 & \ 4 \\
-5 & \ -10 & \ 0 & \ 5 \\
\end{align*}
\]

Figure 4.5: Example inner profile.

Data file for above inner profile

\[
\begin{align*}
0 & \ -3 & \ 0.333 & \ 2 \\
-3 & \ -4 & \ 0 & \ 1 \\
-4 & \ -10 & \ 0 & \ 0 \\
\end{align*}
\]
5. Machining mode such as 1) Turning in radius mode where values of X coordinate represent the actual physical dimensions. 2) Turning in diameter mode where X value is given as twice the actual dimension. 3) 3 axis machining where only graphical display of tool path is performed and simulation of performance indicators is omitted.

Once all inputs are specified, the program reads these input files and loads data contained in them into internal data structures. It also looks for the following files with predefined names in the current working directory.

- **stool.dat**: Contains tool geometry and tool material properties.
- **smaterial.dat**: Contains work material properties.
- **senviron.dat**: Contains data about initial workpiece and cutting tool temperature.
- **scoefffric.dat**: Contains values of coefficient of friction between various combinations of tool and workpiece materials.
- **sgraph.dat**: Contains values of scaling amounts used in fitting polynomials to strain hardening index curves of work material.
- **ssigma.dat**: Contains equations of polynomials fitted to unit flow stress curves of work material.
- **sstrain.dat**: Contains equations of polynomials fitted to strain hardening index curves of work material.
Figure 4.6: General flow control of the simulation tool: 1 of 4
Simulate NC Program

START

- Get operation mode such as diameter mode turning or 3D machining
- Get name of file containing NC program
- Open work piece profile description files and load them into memory
- Load machining environment, work material, cutting tool, m/c setup data into memory
- Load NC program from file into memory
- Compute tool path range and workpiece range in world coordinates
- Create display windows
- Initialize default values for display variables and display them

Figure 4.7: General flow control of the simulation tool: 2 of 4
Figure 4.8: General flow control of the simulation tool: 3 of 4
Simulate NC block

START

load NC block from array into structure

process NC block

load NC block from array into structure

determine tool path

straight line

simulate_line

draw tool path, simulate performance indicators, modify profile.

return

simulate_arc

draw tool path, simulate performance indicators, modify profile.

return

circular

Figure 4.9: General flow control of the simulation tool: 4 of 4
Next the software reads entire NC program and formats and stores it in an array. Then entire NC program is scanned and so is the workpiece profile data to determine the range in world coordinates that need to be displayed. At this point appropriate windows are opened on the computer screen for graphics display. The program now reads each line of the NC program, decodes it and simulates the action generated due to this particular line. This process is repeated till the end of NC program is encountered. The subsequent sections discuss in detail, algorithms used to implement major functions of this simulation tool.

4.3.4 Parsing NC program

The NC program is assumed to be in M and G codes with word address format. Various codes that are recognized by this program are listed in the user manual [30]. The NC program is scanned one line at a time. First, the G codes are parsed and appropriate machining environment parameters are set. Some of the parameters that can be set by G codes are nature of tool motion (linear or circular), cutting speed mode (in rpm or constant surface speed), etc. Next the M code word is decoded. M codes are generally used to control machining processes such as spindle on/off, coolant on/off, tool change, etc. The appropriate action generated by this M code
is displayed on the computer screen to give feed back to the user. Once machining environment variables are set, the program looks for values of cutting speed, feed and cutting tool to be used. The values of X,Y,Z words indicate the new location the cutter has to move in current interpolation mode. If interpolation is linear, a routine to simulate linear tool motion is called to perform actual NC simulation. If interpolation is circular, a routine to simulate circular tool motion is called.

4.3.5 Computation of range of tool motion

Before starting graphical simulation, it is necessary to determine the range of display along X,Y,Z coordinates for scaling purposes. Hence the entire NC program has to be scanned beforehand to determine this. As and when each line of NC program is scanned, the lowest and highest values along X,Y,Z axes encountered so far are stored in respective variables. If circular interpolation is encountered, the X,Y,Z values in that block do not indicate the actual range of tool motion. This is so because this software implements full circular interpolation as against popular one quadrant at a time approach. As an example consider a command to make the cutter move along one full circle. Here the from and to coordinates would be same, and give no indication as to the actual cutter movement along X,Y,Z axes during the circular motion. Hence, for circular interpolation a separate routine is called where, with the knowledge of from and to coordinates and the direction of motion, it is possible to determine the maximum and minimum coordinates along the three axes touched.
by cutter path. Once the entire NC program is scanned, the maximum range value among the three axes is chosen as the tool path range.

4.3.6 Linear interpolation

Linear motion of tool is specified by the coordinates of \textit{from} and \textit{to} points. For simulation of entire tool motion, the intermediate points also need to be determined. The approach used is as below. Transform \textit{from} and \textit{to} points to pixel coordinates of the display window. Determine the axis along which the linear motion extends most. For small increments along this axis compute pixel and world coordinates of these intermediate points and store them in a linked list data structure. Traverse this list from start to end and simulate performance measures at each such location of the cutter.

4.3.7 Circular interpolation

Given \textit{from} and \textit{to} points, direction of motion and the location of center of arc, one can determine the intermediate points. First translate the center of arc to origin. Circle is divided into 4 quadrants called zones and are numbered as shown in Figure 4.10. Determine start zone and end zone of the arc. For example, in clockwise interpolation, a point is in zone 1 if X coordinate is positive and is greater than or equal to Y coordinate. Once start and end zones of the arc are determined, traverse along the X or Y axes from start zone to end zone by small amounts and determine the other coordinates and store them in a linked list. For example consider clockwise
Figure 4.10: Four quadrants of circle as used for circular interpolation

motion starting in zone 1 and ending in zone 4. In zone 1 the arc extends most along Y axis. So in zone 1 and zone 3 determine corresponding X values from small increments or decrements of Y axis. The reverse is the case for zones 2 and 4. For every intermediate pixel coordinate we need to back calculate its world coordinate. From the knowledge of tool path range in world coordinates and window width in pixels, it possible to determine real world length represented by each pixel. We also know the pixel as well as world coordinates of the start point of arc. With this knowledge every adjacent pixel coordinate determined, one can compute its world coordinate by incrementing the previous known world coordinate by a signed amount determined by multiplying the difference in pixel coordinates of current and previous points by real world length per pixel.
4.3.8 Determination of width of cut

The models used to simulate performance measures require width of cut. This is not available directly from the NC program. Hence at every stage of simulation the current width of cut is determined from cutter location and current workpiece profile. To begin with, initial work piece profile data is input to the system as a linked list of straight line segments. Circular profile is approximated by tiny straight line segments. Details of profile input information are available in the user manual [30]. Width of cut for a given cutter location is determined by traversing the work profile list segment by segment till that segment in which the cutter location falls is identified. At this stage, the difference in X coordinate values of cutter location and workpiece profile gives the width of cut. One exception is during grooving or parting during which the effective width of cut is the effective width of the cutting edge. Profile of cutting edge during grooving and parting is assumed to be straight line parallel to Z axis. In those cases where the cutter location is exactly at a point where two different profile segments meet, the segment which is to be considered to determine width of cut is decided as follows. Choose that segment in which the cutter was, just a while ago. For example in case (a) of figure 4.11 width of cut is positive and in case (b) width of cut is negative.
Figure 4.11: Ambiguity in determining width of cut

4.3.9 Computation of cutting speed and depth of cut

The mathematical models to compute cutting force and temperature require cutting speed to be given in meters per second and depth of cut in orthogonal turning is given by feed per revolution. The NC program might contain values of cutting speed in either revolutions per minute or in constant surface speed. The simulation program computes cutting speed from values of revolutions per minute and distance of cutter from the axis of rotation. Similarly feed per revolution can be calculated, given values of feed per minute, constant cutting speed, and distance of cutter from axis of rotation.

4.3.10 Computation of tool usage time

Tool usage time is monitored to determine the change in wear land on tool flank due to cutter wear. For every small change in cutter location, a new set of machining performance indicators are estimated. One of them is tool wear rate. Wear rate is
a function of current length of wear land. Current length of wear land is estimated as the sum of previous wear land and change in wear land during the time between previous computation of wear rate and the time at which current computation is performed. The amount of time elapsed during this period is computed as the distance traveled by tool during this time divided by feed per unit time. The function to simulate wear rate computes wear rate and change in wear land length for a tool usage period of one second. Hence if the time period is \( n \) seconds, the wear rate per second obtained is multiplied \( n \) times to determine current values of wear rate and land length. Size of wear land increases with time and when a tool change occurs, current wear land is stored in tool data file.

4.3.11 Computation of cutting force and temperature

The algorithm developed by Oxley [14] to compute cutting force and tool chip interface temperature is used in this simulation tool. This algorithm is based on orthogonal machining theory as presented by Oxley [16] and is given in Figure 3.3. As the algorithm is self explanatory, detailed description of it is omitted. In this simulation tool a slightly toned down version of the above algorithm is used to improve real time performance of the simulation. The two inner most loops which iterate till temperatures reach steady state are used to take into effect the change in specific heat and thermal conductivity of chip with change in its temperature. The values of temperature obtained this way and those obtained by assuming specific heat and
thermal conductivity to remain same over the range of temperature rise do not differ significantly. Hence in this tool the two inner loops are omitted. The force model used requires work material flow stress properties of workpiece at various temperatures and strain rates in order to determine forces. Such data is available currently for few materials. Oxley et al. used the concept of velocity modified temperature to combine the effects of strain rate and temperature into a single parameter called velocity modified temperature. Unit flow stress and strain hardening values of a material are given as a function of this velocity modified temperature. The curves represented by this function are shown in figure 3.2. These curves are represented mathematically using sections of polynomials and they are used in this tool to calculate values of flow stress and strain hardening index. In addition to calculating forces and temperature this tool also predicts onset of built-up edge and plastic deformation of cutting edge. In finishing operations, the presence of built-up edge is detrimental to surface finish and dimensional accuracy. Oxley [14] presented a theory by which onset of built-up edge can be predicted. According to him, when the value of $T_{mod}$ at tool-chip interface is beyond the dynamic strain aging range (hump in figure 3.2), the layer of chip material adjacent to the interface that has highest temperature is the weakest. Hence, deformation occurs in this layer. But when $T_{mod}$ is within the dynamic strain aging range, flow stress does not decrease with increase in temperature. Therefore, deformation occurs at a distance away from tool-chip interface where temperatures are in the range of least flow stress. Hence built-up edge occurs at this temperature.
In addition to wear, cutting tool can also fail due to plastic deformation of cutting edge resulting from high temperature and stress on it. At any given tool-chip interface temperature if the normal stress on tool (i.e. $\sigma_N$) is greater than or equal to the hot compressive strength of cutting tool at this temperature, we can assume plastic deformation of cutting edge to occur.

4.3.12 Simulation of tool wear

This software estimates wear rate of tool flank. Flank wear is a result of cumulative effect of adhesive and diffusive wear. According to Asibu [23], whose model is used for this software, flank wear rate is a function of tool wear land. The formulas predict wear rate in millimeters per second. Hence the cutting time between previous calculation of wear and present one is computed and supposing it is $n$ seconds, the calculation of wear is performed $n$ times one for each second. After each calculation the wear land value is updated and this value is used for next iteration. We predict a rapid deterioration in tool life after a point where the diffusion wear rate exceeds adhesive wear rate.

4.3.13 Determination of chip formation and surface finish

These calculations are simple and straightforward as mentioned in sections 3.3 and 3.4.
4.3.14 Determination of workpiece profile

At every stage of simulation, current workpiece profile geometry is computed and stored, to determine width of cut. After simulating every aspect of tool motion generated by current NC block, the changes to workpiece profile as a result of this tool motion are determined and profile data is modified accordingly. To begin with, equation of current tool path is computed in terms of its slope and intercept on ordinate axis. The coordinate axes are as shown in figure 4.12. These computed values are stored in a data structure. As described earlier, the profile is represented as a list of line segments where each segment is a straight line equation of the form $y = mx + c$ where $m$ is the slope and $c$ is the intercept value on the ordinate axis. In the algorithm used to modify profile, profile list is examined segment by segment to check if the current path alters this part of profile as represented by this segment. If tool path affects this segment, its structure is modified else next segment is examined. This process is repeated until end of profile list is encountered. Figure 4.12 lists several ways tool path and profile can interact and the new profile generated as a result. To begin with, coordinates of range overlap of tool path and current profile segment are determined and stored in a structure. The range-overlap is determined by sorting the coordinates of profile segment and from and to coordinates of tool path in ascending order. The middle two of the four sorted coordinates determine the range-overlap. The point of intersection of tool path and profile segment is also determined. Now
the profile segment can be altered depending on how the tool path modifies it. A Detailed explanation of the algorithm can be found in the technical manual [31].

4.3.15 Graphical display of simulated variables

In this section details of algorithm used for graphical display of simulated variables such as force, wear, etc. are described. Each of these simulated values is displayed in a separate window which is capable of displaying the current value and previous 30 simulated values. Each time a new value is to be displayed the left most value is removed and the rest of the window contents are scrolled left one position and the new value is displayed in the right most position of the window. The whole process gives a visual effect as though the contents of the window are scrolling from right to left. This effect is achieved by implementing the algorithm in the following way. All the 31 simulated values are stored in a linked list. Initially the whole list is traversed link by link and its contents are displayed in the window. When a new simulated value arrives, it is added to the end of the list and it is traversed again from start to end. This time the link that is being examined is displayed in the window background color. Its effect on the window is that the left most value disappears. In its position display the contents of next link in foreground color. Repeat this process for every link in the list. At the end, delete the first link from the list.
Figure 4.12: Change of profile segment due to current tool path
4.4 Assumptions and limitations

To limit the scope of work, some assumptions were made. In its present version, the software can simulate performance indicators for turning operations only. It can be extended to cover three dimensional machining, by representing the workpiece in terms of solid model and use of solid geometry. We have also assumed a fixed coordinate system as described in the user manual. Currently performance indicators are computed for turning, boring, grooving and parting only. Other operations such as drilling, threading, chamfering are not being considered. Roughing cycles for turning, boring and grooving are not recognized by this tool, the reason being that format for these blocks differ from machine to machine and moreover a simple function can be written to translate them into series of canned cycles. Since we have chosen to implement full circular interpolation, the program expects the I,J values to be signed, to avoid ambiguity. Some other important assumptions are as below. All of these assumed values can be changed by modifying the appropriate variables in the header file for global variables and recompiling the application.

1. Maximum size of the program is assumed to be 500 lines.

2. Number of tool slots on the turret is assumed to be 15.

3. Number of temperature ranges assumed for work material flow stress properties is 8.

4. Assumed maximum feed in inches per minute is 400.
5. Assumed maximum feed in mm per minute is 10080.

6. Assumed minimum feed in inches per minute is 0.003.

7. Assumed minimum feed in mm per minute is 0.0762.

8. Assumed maximum cutting forces that can be displayed in the display window is 6000 Newtons.

9. Assumed maximum wear rate that can be displayed in the display window is 0.001 meters per second.

10. Assumed tool chip interface temperature that can be displayed in the display window is 3000 Celcius.

11. Assumed worst surface finish that can be displayed in the display window is 100 microns.

12. Assumed maximum wear land that can be displayed in the display window is 3mm.

13. Tool motion is considered to be rapid if feed is greater than 30% of assumed maximum permissible feed.
CHAPTER 5

Summary and conclusions

This work is an attempt at enhancing the extent and scope of NC verification. We developed a software tool which presents to the user a graphical display of tool path as well as dynamic display of simulated values of machining performance indicators such as cutting force, temperatures, wear, surface finish and chip formation. The inputs required to simulate above values can be obtained from NC program, initial workpiece profile information and workpiece and tool material data. From the literature survey conducted it was found that most of the workpiece and cutting tool material data required for the above software tool are currently available, though from different sources. The exception being work material flow stress properties at high strain rates which were available for only few compositions of low carbon steels. For simulating cutting forces and tool chip interface temperature, the models developed by Oxley et al. were used. For tool wear rate, the model developed by Kannatey-Asibu Jr was used. The surface finish model was taken from that of Mehta and Mittal. For predicting chip formation the model developed by Nakamura, Christopher and Wuebling was used. One important input parameter that is required by most of the simulation models but cannot be obtained from NC code is width of cut. In this
work, the width of cut was obtained from the knowledge of current workpiece profile and location of cutter. Based on the initial description of work profile the current profile as affected by tool motion is computed by use of simple analytical geometry. The accuracy of the simulated values depends on the models used. Literature survey again reveals that models to predict forces, temperatures and tool wear with reasonable accuracy for a range of cutting conditions are currently available. But in the case of surface finish and chip formation not many models were found. From this work it can be concluded that scope of NC verification can be extended beyond mere graphical display of tool path. By using theoretical models to predict performance indicators the models can be used for a wide range of cutting conditions. Most of the data required for these models are currently available and it would be cheaper and more useful to generate machinability databases based on these models rather than conventional empirical machinability databases. The simulation tool can be extended to cover three dimensional machining by first representing the work piece in 3D form and use of solid geometry and heuristics to determine width of cut.
Appendix A
Figure A.1: Snapshot of a simulation run suggesting onset of builtup edge.
Figure A.2: Snapshot of a simulation run suggesting abnormal wear rate of flank.
Figure A.3: Snapshot of a simulation run showing grooving and circular cutting.
REFERENCES


