Tool life prediction and management for an integrated tool selection system

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To my family

TOOL LIFE PREDICTION AND MANAGEMENT FOR AN INTEGRATED TOOL SELECTION SYSTEM

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ABSTRACT

In machining, it is often difficult to select appropriate tools (tool holder and insert), machining parameters (cutting speed, feed rate and depth of cut) and tool replacement times for all tools due to the wide variety of tooling options and the complexity of the machining operations. Of particular interest is the complex interrelationships between tool selection, cutting data calculation and tool life prediction and control.

Numerous techniques and methods of measuring and modelling tool wear, particularly in turning operations were reviewed. The characteristics of these methods were analysed and it was found that most tool wear studies were self-contained without any obvious interface with tool selection. The work presented herein deals with the development of an integrated, off-line tool life control system (TLC). The tool life control system (TLC) predicts tool life for the various turning operations and for a wide variety of workpiece materials. TLC is a closed-loop system combining algorithms with feedback based on direct measurement of flank wear. TLC has been developed using *Crystal*, which is a rule-based shell and statistical techniques such as multiple regression and the least-squares method. TLC consists of five modules namely, the technical planning of the cutting operation (TPO), tool life prediction (TLP), tool life assessor (TLA), tool life management (TLM) and the tool wear balancing and requirement planning (TRP).

The technical planning of the cutting operation (TPO) module contains a procedure to select tools and generate efficient machining parameters (cutting velocity, feed rate and depth of cut) for turning and boring operations. For any selected insert grade, material sub-class, type of cut (finishing, medium-roughing and roughing) and type of cutting fluid, the tool life prediction (TLP) module calculates the theoretical tool life value (T_{sugg}) based on tool life coefficients derived from tool manufacturers' data. For the selected operation, the tool life assessor (TLA) generates a dynamic multiple regression to calculate the approved tool life constants ($lnC, 1/\alpha, 1/\beta$) based on the real tool life data collected from experiments. These approved constants are used to calculate a

modified tool life value (T_{mod}) for the given operation. The stochastic nature of tool life is taken into account, as well as the uncertainty of the available information by introducing a 95% confidence level for tool life.

The tool life management module (TLM) studies the variations in tool life data predicted by TLP and TLA and the approved tool life data collected from the shop floor and provides feedback concerning the accuracy of tool life predictions. Finally, the tool life balancing and requirement planning (TRP) methods address the problem of controlling and balancing the wear rate of the cutting edge by the appropriate alteration of cutting conditions so that each one will machine the number of parts that optimize the overall tool changing strategy. Two new tool changing strategies were developed based on minimum production cost, with very encouraging results.

Cutting experiments proved that the state of wear and the tool life can be predicted efficiently by the proposed model. The resulting software can be used by machine manufacturers, tool consultants or process planners to achieve the integrated planning and control of tool life as part of the tool selection and cutting data calculation activity.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

η	Machine tool efficiency factor
ε	Random error
σ^2	Variance
μ	Circumferential friction coefficient of the chuck jaw
A	Chip cross section area (mm^2)
a	Depth of cut (mm)
$a_{c\,max}$, $a_{c\,min}$	Maximum and minimum depths of cut due to chip-breaking (mm)
a_{max}	Maximum feasible depth for roughing (mm)
a_{stock}	Maximum stock (mm)
$a_{t\,max}$	Maximum allowable depth of cut for tool (mm)
C, α, β, γ	Coefficients in the extended Taylor equation
C_b	Cost per batch (£)
clmdia	Clamping diameter (mm)
clmlen	Clamping length (mm)
C_p	Cost per cutting operation (£)
cpdia	Cutting point diameter (mm)
cpdist	Cutting point distance from clamping point (mm)
C_{pr}	Production cost (£)
D	Effective machining diameter (mm)
d.o.f	Number of degrees of freedom
defcom	Maximum allowable component deflection (mm)
D_{ext}	External diameter (mm)
D_{int}	Internal diameter (mm)
E	Young's module of elasticity (N/mm^2)
elc	Stiffness of the workpiece ($N\ mm^2$)
f_a	Force component in the direction of the depth of cut (N)
f_{axial}	Axial cutting force (N)

f_g	Static clamping force of the chuck jaw (N)
f_{radial}	Radial cutting force (N)
f_s	Force component in the direction of the feed rate (N)
f_v	Force component in the direction of cutting velocity (N)
f_{v1}, f_{v2}, f_{v3}	Maximum velocity force due to: circumferential slip, component thrown out, power (N)
K, ψ	Tool approach and trailing angles (°)
K_{corr}	Correction factor for feed rate
K_M	Machining cost (£)
K_S	Work set up cost (£)
K_{sm}	Specific resistance to cut for the material (N/mm^2)
K_T	Tool changing cost (£)
K_W	Tool wear cost (£)
l_e	Length of the cutting edge (mm)
n	Rotational spindle speed (rpm)
N_e	Required number of edges under the current conditions
N_{mc}	Number of multiple coincidental machine stops.
n_{max}	Rotational spindle speed for maximum power (rpm)
n_{passes}	Number of passes
N_S	Number of machine stops for tool changing
P_{max}	Maximum spindle power (kW)
q	Batch size
R_a	Surface roughness (μm)
r_e	Tool nose radius (mm)
rnc	Number of components an edge can machine
s	Feed rate (mm/rev)
S^2	Residual variance
$s_{c\,max}$, $s_{c\,min}$	Maximum and minimum feed rates due to chip-breaking (mm/rev)

s_{max}	Maximum feasible feed rate (mm/rev)
$s_{r\ max}$	Maximum allowable feed rate for the tool (mm/rev)
t_1	Component set up time (min)
t_2	Machining time (min)
t_3	Worn tool changing time (min)
T_{app}	Approved tool life from shop floor (min)
T_{mc}, T_{mt}	Tool life: minimum cost, minimum production time (min)
T_{mod}	Modified tool life by TLA (min)
t_{pr}	Production time (min)
T_r	The measured tool life (min) for a given cutting velocity (v_r m/min)
t_s	machine stopping time (min)
T_{sugg}	Suggested tool life from TLP (min)
v	Cutting velocity (m/min)
$v_{max,power}$	Cutting velocity for maximum spindle power (m/min)
v_{mc}, v_{mt}	Cutting velocity: minimum cost and minimum production time (m/min)
w	Number of batches.
x	Cost rate of the machine tool (£/min)
y	Cost per cutting edge (£)
$\mathbf{Y}, \mathbf{X}, \mathbf{x}, \boldsymbol{\theta}$	Matrix notations

Chapter 1

INTRODUCTION AND LITERATURE REVIEW

1.1 TOOL SELECTION WITHIN PROCESS PLANNING

Tooling technology is a vital element of any machining process. It has a strong interface with process planning since the key tasks of tool selection and the definition of how tools should be used (i.e. the calculation of cutting conditions) are essential elements of the process planning activity [Maropoulos 1995]. The tool selection process comprises both geometric and machining technology considerations. The geometry and area clearance capability (feed directions) of cutting tools define their suitability for generating the geometric features of a component. The geometric capability of tools is taken into account during the initial stages of process planning and influences the definition of operation types and machining volumes as well as the subsequent sequencing of cutting operations.

Machining industry saw their tooling portfolio increase since tool suppliers vie to produce better tools for this or that workpiece material or type of operation. Since the start of the 1980s tool management has become an important consideration for machinists. The first step towards comprehensive tool management is the development and implementation of a tool selection system. The reason is that it is impossible to manage the tooling resource without controlling the initial selection of tools. A prototype intelligent tool selection (ITS) system is under development at Durham University [Maropoulos 1992]. ITS has five conceptual levels covering all tool considerations from the initial selection for an operation, to tool rationalisation and allocation to machines. Figure 1.1 shows the overall layout of the selection system and the interacting technologies at each level. It is evident that the selection process starts by applying local considerations relative to an operation/component and it gradually becomes wider by applying criteria in relation to machine tool(s) and finally by considering the tools in the general optimization context of the shop-floor [Maropoulos 1992].

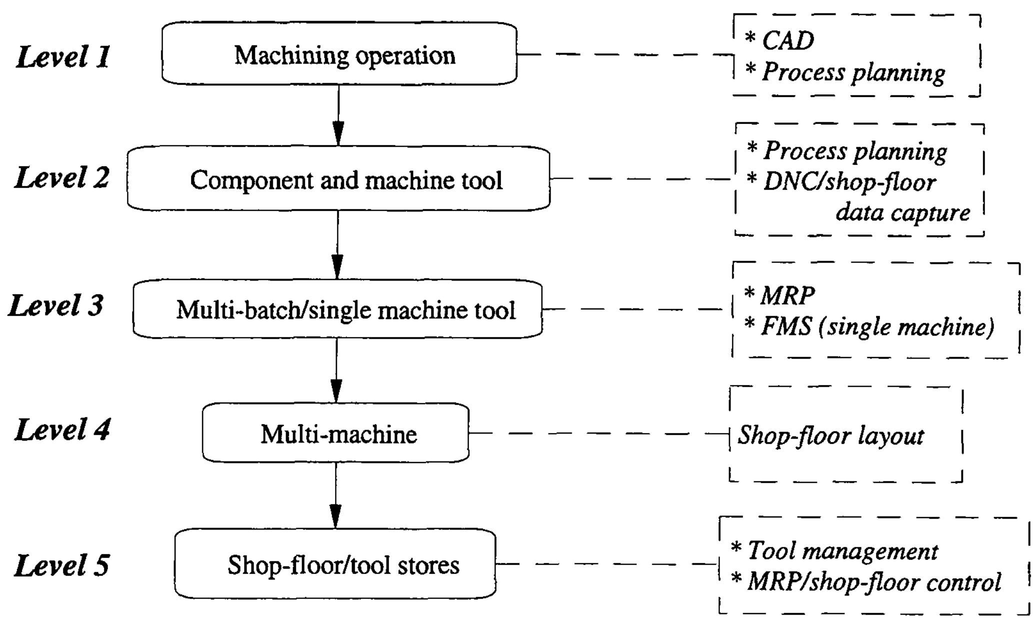

Figure 1.1 ITS tool selection levels and interacting technologies [Maropoulos 1992]

The first tool selection level belongs to the realms of process planning. The aim at this level is to provide tools that can produce the required geometry and machine the workpiece material efficiently whilst satisfying all quality assurance considerations. Several operations may be specified on a given component and tools are selected for each operation. The second level has the same time cycle as process planning and the main considerations applied here are the number of tools required for fully machining a component and the definition of the optimal tool replacement strategy. The third selection level is activated when a variety of batches of different components, in terms of geometry and/or material, are to be machined on the same machining centre using one set of tools. The central requirement here is to reduce tool set-up times based on material orders and schedules produced by the material requirement planning (MRP) system. Having completed the first three tool selection levels, there is a set of tools allocated to each machine tool for machining either a certain product *(Level 2)* or a product range *(Level 3)* over a given period of time. The fourth level performs the final tool rationalisation and produce the final tool resource structure (TRS) of components planned by MRP. Having completed the four selection levels, sets of tools are allocated either to stand-alone machines *(Levels 2 and 3)* or the sections of the shop-floor *(Level 4)*. The fifth level is very much a planning phase and its various functions have widely different time cycle. The main objectives of the fifth level are to reduce tool inventory, define the overall tool requirements and manage the efficient allocation and distribution of tools to machining resources [Maropoulos 1992].

Obviously, the performance-based selection of tools requires the modelling and optimization of the machining process, and in that respect tooling technology interfaces closely with process modelling techniques. The initial testing of ITS in industry and the laboratory gave very encouraging results [Maropoulos and Gill 1995; Maropoulos and Alamin 1995]. This Thesis includes the tool life prediction and management aspects of tool selection.

1.2 TOOL LIFE CONTROL AND MANAGEMENT WITHIN TOOL SELECTION

The efficiency of the tool management system is a main concern in any modern machining environment. ITS supplies the optimal tool or set of tools for each of the turning operations required to machine a component of any geometry and production complexity. During the selection of turning tools, ITS calculates the machining time, cost and percentage tool wear for each machining operation [Maropoulos and Hinduja 1989]. When the tool wear rate per component is known, the number of components a certain tool can machine before its insert must be replaced can be calculated. For a given combination of workpiece material and tool material, the tool wear rate is a function of the cutting conditions. ITS calculates cutting data for every selected tool and is can predict the tool life in each case. This can be used for planning the requirements for consumable tools, optimizing the tool changing policy and avoiding catastrophic tool failures. Additionally, when finishing operations are performed it is preferable to complete the operation using one tool since the surface texture produced by the new insert will differ from that produced by the previous tool. Therefore, the aim of the present research is to develop a tool life control system (TLC) which will form a part of a larger tool selection system. TLC will study and analyse the stochastic nature of tool life using tool life data collected from a large number of experimental tests and data supplied by tool manufacturers. The major reasons for developing TLC are:

- The use of tool life data in selecting tools for different component materials.
- The use of tool life relationships in optimization studies to obtain economic cutting conditions.
- The improvement of product quality control.
- The fundamental need to predict optimal tool replacement strategy. An autonomous tool replacement strategy must be effective and reliable to exploit tool life and prevent failure.
- The calculation of accurate carbide requirements for machining a given range of workpiece materials.

Initially, TLC predicts tool life from theoretical calculations based on data supplied by tool manufacturers. These predictions are then validated by using approved information collected from the shop floor. In this respect, TLC is a data driven, closed loop system since it uses tool life information from experiments or the shop floor.

1.3 TOOL WEAR AND TOOL LIFE: DEFINITION AND THEORY

One of the most important elements of any machining system is the cutting tool; this has to withstand the high temperature and pressure imposed on it by the moving workpiece and chip without undergoing degradation or change in shape [Gane and Stephens 1983].

Tool wear is a complex and varied process that cannot be described by a single, simple mechanism. The locations and extent of wear are different, changing with tool material, operation, cutting conditions and workpiece material. Different areas of the same tool may involve different wear mechanisms because the temperature, sliding velocity and stress are different [Trent 1991, Tipnis 1980]. The two variables having a major effect on the wear rate of the tool are the temperature and the normal pressure on the face of the cutting tool [Boothroyd 1989]. Tool life is an important factor in the evaluation of machinability because it directly influences machine set-up time, down-time, cost of tool changing and the cost of the tool itself.

This study focuses on single point cutting tools and tool life is considered to be equivalent to the life of a single cutting edge. Herein, the word tool is used to denote a cutting edge. The edge of the cutting tool will reach the end of its useful life due to excessive wear or breakage, which may occur as a gradual process or as a sudden chipping or fracture. Tool wear usually results in a loss of dimensional accuracy of the finished product, a reduction in the surface finish quality and possible damage to the workpiece, any of which may result in scrapped products. Hence, it is essential to know when a tool needs to be replaced by a new one. In metal cutting the failure of the cutting tool can be classified into two broad categories, according to the failure mechanisms involved [De Garmo 1988].

- *Slow-failure mechanisms*: gradual tool wear on the flank(s) of the tool (flank wear) or on the rake face of tool (crater wear) or both.

- *Sudden-failure mechanisms*: rapid, usually unpredictable and often catastrophic failure mechanisms resulting in the abrupt, premature failure of a tool.

The *sudden-failure mechanisms* are categorised as plastic deformation, brittle fracture, fatigue fracture, or edge chipping. Here again, it is difficult to predict which mechanism will dominate and result in a tool failure in a particular situation. Therefore, tool life should be treated as a stochastic variable and not as a deterministic quantity.

Present tool replacement policies appear to offer large margins for machining economics improvement [Levi and Rossetto 1978]. Harris et al. (1989) and Kramer (1987), further emphasised the advantages of close tool life monitoring. Maropoulos (1988) and La Commare et al. (1983) stated that it is essential in machining to find tool replacement policies that can be used to minimize the machining cost per workpiece and they proposed different techniques for determining optimal cutting conditions with different tool replacement strategies.

1.3.1 Mechanisms of wear

The wear mechanisms during machining include abrasive and adhesive wear, diffusion wear, wear arising from electrochemical action and surface fatigue wear.

- *Wear by Abrasion*

The most common type of tool wear is that of abrasion where the relative motion between the underside of the chip and the tool's face as well as between the newly cut surface and the tool's flank, cause the tool to wear. Abrasive wear normally causes the development of a flank wear land on the flank face of the tool.

- *Wear by Adhesion*

Adhesion or pressure welding occurs between the face of the tool and the underside of the chip under all cutting conditions. Adhesive wear is primarily a wear mechanism on the rake face of the tool, and usually occurs at low cutting velocities when an unstable built-up-edge is likely to be present on the rake face of the tool [Trent 1991]. For those conditions where only a built-up-layer or a stable built-up-edge is formed, although adhesion will occur, it will not result in the removal of tool material. When built-up-edge detaches itself from the tool face it carries with it small quantities of tool material due to the strong bonding between the built-up-edge and the tool material.

- *Wear by Diffusion*

Diffusion wear is caused by a displacement of atoms in the metallic crystal of the cutting edge from one lattice point to another. Diffusion is accelerated by the high temperatures generated by the rapid movement of the work material over the tool's surface. The surface properties of the tool are altered with the diffusion of atoms from the material and this results in accelerated crater wear.

- *Wear by Electrochemical Action*

Under appropriate conditions, normally caused by the presence of a cutting fluid, it is possible to set up an electrochemical reaction between the cutting tool and the workpiece material which results in the formation of a weak, low shear strength layer on the face of the tool. Whilst this can have a desirable effect, because it reduces the friction force acting on the cutting tool and results in a reduction of the cutting forces and temperatures, it will also result in small amounts of tool material being carried away by the chip leading to increased wear.

- *Wear by Fatigue*

Fatigue wear is only an important wear mechanism when adhesive and abrasive rates are small and there is a cyclic loading on the cutting edge. Surfaces which are repeatedly subjected to cycling loading and unloading may gradually fail by fatigue leading to detachment of parts of the surface. This situation can arise in intermittent cutting which may also cause edge chipping. Nucleation of subsurface fatigue cracks may be initiated by subsurface defects such as non-metallic inclusions [Kalpakjian 1992]. Fatigue cracking does not normally occur if the stress is below a certain limit. Since the contact pressure is determined by the yield properties of the workpiece material, fatigue wear can be reduced by using cutting tools which are appreciably harder and tougher than the workpiece [Kalpakjian 1992].

1.3.2 Types of wear

Due to the interaction of the chip and tool, which takes place at high pressures and temperatures, the tool will always wear. As the tool wears its geometry changes. This geometry change influences the cutting forces, the power being consumed, the surface finish and dimensional accuracy obtained and the dynamic stability of the process. The progressive wear of the cutting tool can take several forms.

- *Flank wear*

Wear on the tool flank in the form of a wear land generated as the newly cut surface of the workpiece rubs against the cutting tool as shown in Figure 1.2.

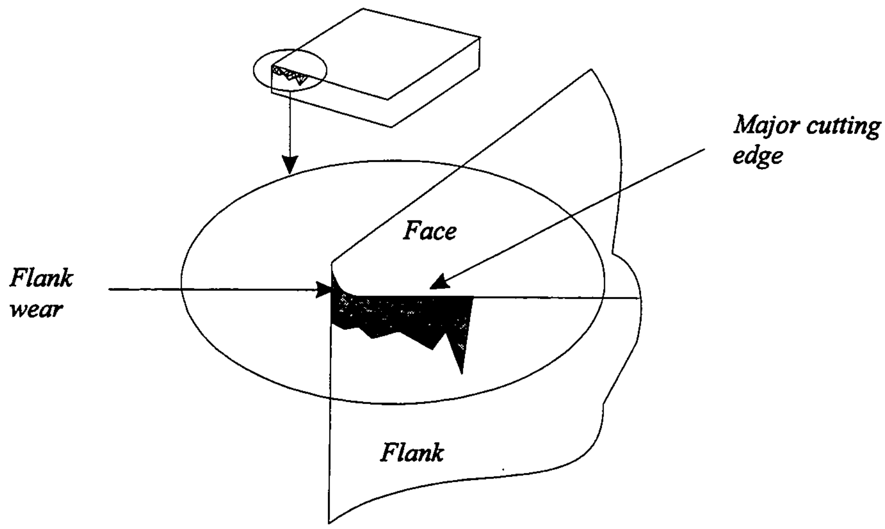

Figure 1.2 Flank wear on an indexable insert.

- *Crater wear*

Tool wear on the rake face of the tool is characterised by the formation of a depression or crater which is the result of the chip flowing over the tool's rake face. Because of the stress distribution on the tool face, the frictional stress in the region of sliding contact between the chip and the tool is at a maximum at the start of the sliding contact region and zero at the end [Mills and Redford, 1983]. This results in localised pitting of the tool's face some distance up the face which is usually referred to as cratering and normally has a section in the form of a circular arc as shown in Figure 1.3.

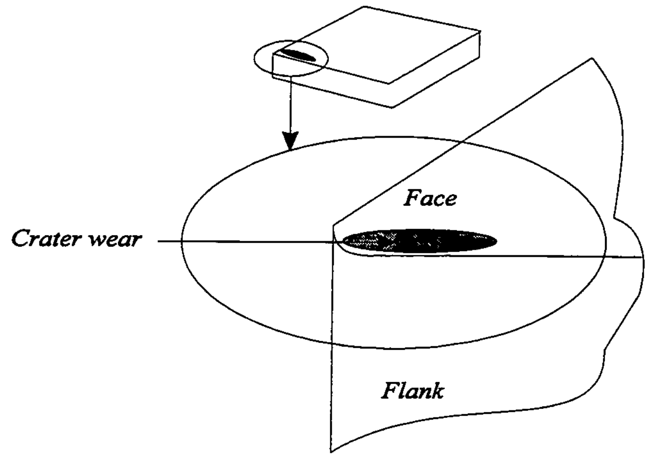

Figure 1.3 Crater wear on an indexable insert.

- *Notch wear*

At the end of the major flank wear land, where the tool is in contact with the uncut workpiece surface it is common for the flank wear to be more pronounced than along the rest of the wear land as shown in Figure 1.4. This is because of localised effects such as a hardened layer on the uncut surface caused by work hardening introduced by a previous cut, presence of an oxide scale, and localised high temperatures resulting from the edge effect [Trent 1991]. *Notch wear* may lead to total tool failure.

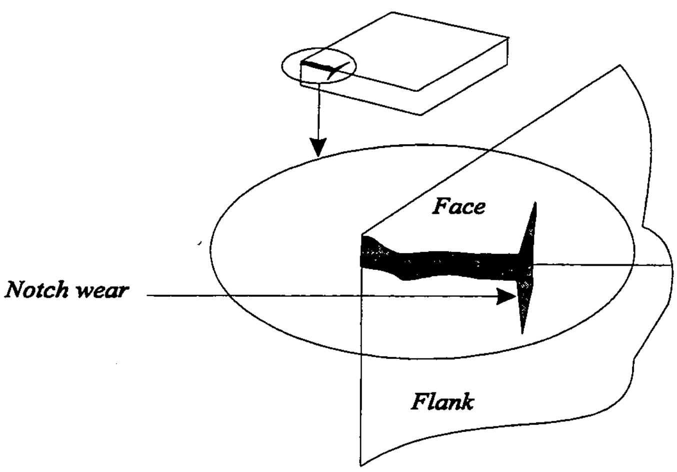

Figure 1.4 Notch wear on an indexable insert

- *Edge rounding*

The major cutting edge may become rounded by abrasion. Cutting then proceeds with an increasingly negative rake angle towards the root of the cut. When the undeformed chip thickness is small, cutting action may cease and all energy may be expended in plastic or elastic deformation [Hoshi 1981]. Problems with edge rounding may be avoided, at least when hard tools are used, by grinding a double rake so that the cutting proceeds with a stable built-up-edge (BUE).

- *Edge chipping*

This may be caused by periodic break-off of the BUE or when a brittle tool is used in interrupted cuts. In this process surface finish suffers and the tool may finally break.

- *Edge cracking*

Thermal fatigue may cause cracks to form parallel or perpendicular to the cutting edge of brittle tools *(Comb cracks).*

- *Catastrophic failure (Tool breakage)*

Tools made of more brittle materials are subject to sudden failures (breakage). This is a problem of all brittle materials such as ceramics and cemented carbides, especially in interrupted cuts.

1.3.3 Progressive tool wear

For progressive wear, the relationship between tool flank wear and time follows the pattern shown in Figure 1.5. Initially, with a new tool, the tool wear rate is high and is referred to as primary wear. It was suggested [Redford 1980] that the high rate of wear in the primary wear stage is due to edge crumbling. The duration of primary wear is dependent on the cutting conditions. However, for a given workpiece material the amount of primary wear is approximately constant, but the time in which it is produced decreases as the cutting velocity is increased. This wear stage is followed by the secondary wear stage where the rate of flank wear is constant but considerably less than the rate of primary wear in the practical cutting velocity range. At the end of the secondary wear stage, when the flank wear land is considerable and far greater than that recommended as criterion for tool failure, the conditions are such that a second rapid wear rate phase commences and this, if continued, rapidly leads to tool failure (tertiary stage).

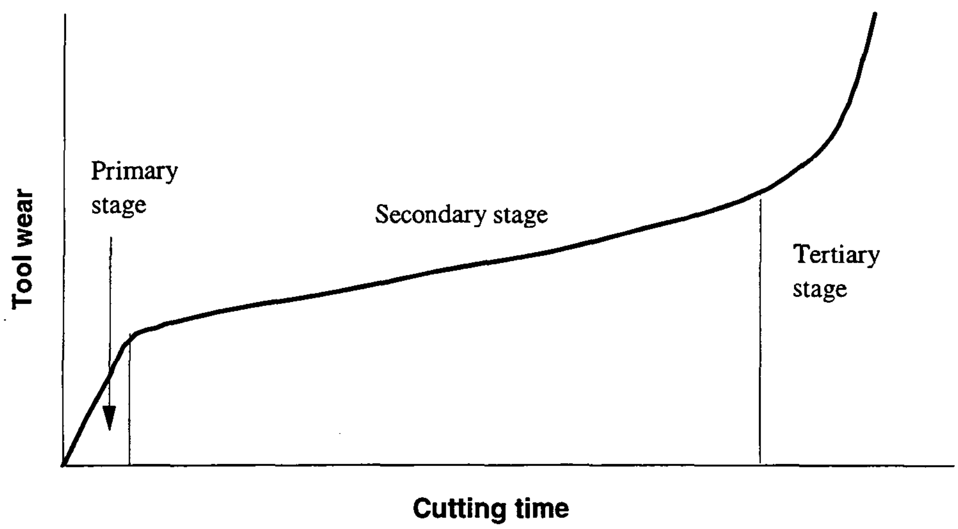

Figure 1.5 Typical relationship between flank wear and cutting time.

If any form of progressive wear were allowed to continue into the tertiary stage, the tool would fail catastrophically resulting in scrapped component and probably causing damage to the machine tool. For carbide cutting tools, the tool is said to have reached the end of its useful life long before the onset of the tertiary stage. Usually, the tool is removed after a given amount of wear is produced on the flank of the tool.

1.3.4 Parameters influencing tool wear and tool life for turning

The rate of material removal from the workpiece increases with increasing cutting velocity, feed rate and depth of cut. However, increased cutting conditions result in reduced tool life. The identification of the relationship between tool wear (and tool life) and cutting conditions is therefore essential for the economic utilization of cutting tools. *F. W. Taylor* (1907) in his classic paper "On the art of cutting metals" suggested that, for progressive wear, the relationship between the time to tool failure for a given wear criterion and cutting velocity was of the form:

$$v\,T^{-1/\alpha} = C_1 \qquad (1.1)$$

where; v is the cutting velocity (m/min), T is the tool life (min), and α and C_1 are constants for a particular tool-workpiece combination. This basic relationship was later extended to the more general form:

$$T = \frac{C_2}{v^{1/\alpha}\, s^{1/\beta}\, a^{1/\gamma}} \qquad (1.2)$$

Where; T is the mean tool life (min), v is the cutting velocity (m/min), s is the feed rate (mm/rev), and a is the depth of cut (mm). C_2, α, β , and γ are constants which depend on the tool and workpiece materials.

Tool life is affected less by changes in the depth of cut rather than by changing either the feed rate or the cutting velocity. The consensus of most authorities in material removal is that the best method of increasing the material removal rate is to use the deepest cut possible [Maropoulos 1992]. Depth of cut, however, is limited by the amount of stock to be removed, machine power capability, rigidity of the set-up, tooling capability, surface finish and sometimes by the shape of the workpiece. Also, it is generally recommended that only 50 –75% of the cutting edge should be utilized during cutting.

Changes in the feed rate have a greater effect on the tool life than changes in the depth of cut, but lesser effect than changes in cutting velocity. Increases in feed rates are limited by the capability of the machine tool, cutting tool, workpiece, and set-up to withstand the higher cutting forces as well as by the surface finish required in the case of finishing operations.

The cutting velocity has greater effect on tool life than either depth of cut or feed rate and hence velocity selection is critical. The use of higher cutting velocities to obtain increased material removal rates can result in costly penalties with respect to tool life and may be the least desirable means of improving productivity. However, several cutting tool materials, such as coated carbides, ceramics, polycrystalline diamond and cubic boron nitride, can provide benefits because of their higher cutting velocity capability. Higher velocities may also create problems with respect to vibration, the life of certain machine tool components, such as bearings, and reduced safety.

Because of its effects on the quality of the machined surface and the economics of machining, the study of tool wear is one of the most important and complex aspects of machining operations. Whereas cutting conditions are independent variables, the forces and temperatures generated during machining are dependent variables. Similarly, wear depends on the tool and workpiece materials (their mechanical and chemical properties), tool geometry, cutting fluid properties, and the cutting conditions. In addition, the geometry of the tool's entrance and exit during a cut differs from one operation to another. The entrance and exit conditions are of special importance since high stresses are generated on the tool at these points [Pekelharing 1980].

1.4 WEAR MEASUREMENT TECHNIQUES

Tool wear measuring and sensing techniques fall into two categories: *direct* and *indirect* measurement methods [Micheleti and Koenig 1976]. The first category involves the direct optical measurement of wear, such as by observing changes in the tool profile or workpiece dimensions. Other direct methods are by observing the rake-face side of the chip for crater-wear particles and the measurement of wear by radioactive techniques [Cook and Subramanian 1978]. However, a large number of problems are still left to be solved with respect to the reliability and accuracy of direct method. Indirect methods of wear measurement involve the correlation of wear with process variables such as cutting forces [Moriwaki 1984; Tonshoff 1988], cutting temperature [Chow and Wright 1988], surface finish and integrity [Takeyama and Sekiguch 1976], vibration [Jaing and Zhang 1987] and acoustic emission [Metha 1983; Teti 1989]. The most common and reliable technique is the direct observation and optical measurement of wear on the tool. The principle classification of tool wear sensing methods is shown in Table 1.1 [Dan and Mathew 1990].

Table 1.1. Principal classification of tool wear measuring and sensing methods

Method	Procedure	Measurement	Instrumentation
Direct	Optical	Shape or position of cutting edge	TV camera; optical transducer
	Workpiece size	Workpiece dimension	Optical, pneumatic, ultrasonic, electromagnetic transducers
	Tool/work distance	Distance from workpiece to tool	Pneumatic gauge, displacement transducer
	Tool/work resistance	Changes of junction resistance	Voltmeter
	Radioactivity	Radioactive activity	Geiger-Muller tube
	Wear particles	Particle size and concentration	Spectrophotometer; scintillates
Indirect	Cutting forces	Change in cutting forces	Dynamometer
	Acoustic emission	Stress wave energy	AE transducer
	Sound	Acoustic waves	Microphone
	Vibration	Vibration of tools or tool posts	Accelerometer
	Temperature	Variation of cutting temperature	Pyrometer
	Power input	Power consumption	Dynamometer
	Surface roughness	Change in surface roughness	Optical transducer

1.4.1 Direct methods for measuring tool wear

The methods for direct measurement of wear are discussed in this section.

1.4.1.1 Optical measurement

The change in the geometry of the cutting tool is measured by direct mechanical gauging, profile tracers [Deutsch and Wu 1973; Shaw and Smith 1961], weighing, ultrasonic, optical, pneumatic and other related [Gall 1969; Yamazaki 1974] methods. Because of the simplicity and ease of optical measurement, flank wear remains the most commonly used measure of tool wear. Generally, tool life studies apply a wear land length criterion as a measure of a tool's remaining useful life. Except for some special research techniques, a toolmaker's microscope fitted with a measuring scale is all that is needed to visually measure flank wear.

A new method is based on vision technology, in which the tool is illuminated by the beam of a laser and the wear zone is visualised using a Vidicon camera. The image is converted into digital pixel data and is processed to detect the wear land width. Detailed aspects of the image processing procedures are discussed by Jeon and Kim (1988). Fibre optic sensors were also used for in process measurement of flank wear [Giusti and Santochi 1979]. This technique is relatively inexpensive to implement and can be applied to either conventional production lathes or NC lathes. Sata (1979) examined the worn tool by a TV camera at every tool change and the morphology of the tool failure was classified by using a pattern recognition technique. When an undesirable morphology was found, the tool material or the tool geometry was changed according to a decision table which had been constructed in advance by a learning algorithm. Video cameras were also used in monitoring tool wear on NC lathes [Rutteli and Cuppini 1988; Giusti and Santochi 1984]. A tool wear signal collected by a TV camera was processed by a computer and displayed on a video monitor.

In vision measuring techniques, the determination of the worn area is usually based on the high intensity of the reflected light from the worn surface [Daneshmend 1983; Pederson 1988]. The amount of flank wear is then calculated using a threshold binary image, where the worn surface is represented by white, in a black background. Since the flank wear surface is never completely uniform, the intensity of the reflected light from some worn areas is frequently lower than the threshold value. Thus, those areas are incorrectly represented by black. It is, therefore, not trivial to obtain an acceptable binary image which represents the entire flank wear region as white. These methods have the advantages of high measuring accuracy but cannot be adopted for in situ applications mainly because of the interruption of coolant and workpiece. Also there can be instances when it is difficult to detect tool wear lands in the presence of a built-up edge or metal deposits.

1.4.1.2 Workpiece size changing

Except in the case of actual failure, unexpected change in workpiece size is clearly an important criterion which relates to part quality and tool wear. Workpiece size monitoring methods are used extensively in grinding [Sade et al. 1972; Ueno 1972; Wiatt 1963]. Another method uses an electromagnetic sensing probe to measure tool wear by monitoring the change in the workpiece diameter during a turning operation [El Gomayel 1986]. The change in the workpiece diameter gives a voltage output directly related to the gap between the sensor and the workpiece. The main problem with these measuring systems is that it is not possible to distinguish between nose wear and flank wear and errors can be introduced by thermo-expansion of the workpiece or the inaccuracy of the machine tool. Like every other method, this one is also influenced by disturbance factors which reduce the accuracy of the sensing device, such as:

- Most of the electromagnetic probes are heat sensitive. Therefore, all the tests should be planned and performed within a certain temperature limit to avoid further adjustments due to temperature variations on the face of the sensor.
- Discontinuous chips might interfere with the sensor and affect the results.
- Misalignment between the centre in the spindle of the headstock and the live centre in the tailstock.
- Deflection in the live centre or tool holder due to cutting forces.
- Deflection in the workpiece.
- Thermal expansion of the carbide insert and the tool holder.
- Vibration of the workpiece and tool.
- Time delay in measurement since the sensors can not be integrated into a carbide insert.

1.4.1.3 Distance from tool post to workpiece

Generally, the work surface moves towards the tool post as wear progresses in a turning operation. Methods have been developed to measure such a motion using contact measurement [Takeyama and Doi 1967] as well as ultrasonic and air gauges [Bath and Sharp 1968; Stoferele and Bellmann 1975; Suzuki and Weinamann 1985].

Tool wear is detected by measuring the change in distance between the tool holder and work surface using a stylus which is mounted on the tool holder [Suzuki and Weinmann 1985]. The stylus movement is sensed by a displacement transducer. Considerable research has been conducted applying this method [Takeyama 1976]. The results indicate that the accuracy of the sensor is totally dependent upon the accuracy of the slideway motion, the size of the sensor, the compliance of the tooling system (especially in the feed and radial directions) and the change in the feed force. Styluses are likely to be subject to at least one of the following drawbacks:

- Their sensitivity could be directly influenced by the temperature variations of the work surface.
- Their sensitivity could vary with the physical properties of work materials.
- Measurements could be hampered by the use of cutting fluids.

Other various error sources have been identified which could influence the overall accuracy of the sensor. These are:

- Inaccuracy of the tool holder path.
- Tool holder deflection in the feed direction.
- Stylus displacement in the tangential direction.
- Positional alignment of the stylus in the vertical direction.
- Thermal expansion of cutting tool and tool holder.

1.4.1.4 Tool/work junction electrical resistance measurement

The contact area of the tool and workpiece increases with tool wear, so that the electrical resistance of this junction decreases. This principle has been used to sense tool wear [Wilkinson 1971]. Another method used a film conductor bonded onto the tool flank [Uehara 1973]. As the tool wears, part of the conductor wears and the resistance to the current increases and was found to correlate with the flank wear. Problems due to the variation in depth of cut (cutting forces) could complicate the contact resistance and introduce an error in the measurement.

1.4.1.5 Radioactive techniques

This method involves attaching or implanting a small quantity of radioactive material to the flank of the tool. At the end of each cutting cycle the tool is monitored with a Geiger-Muller tube to determine whether the radioactive implants are still there. When no signals are received the wear land has progressed beyond the point which means that the tool has failed. Most of these methods are slow and not particularly safe off-line methods [Cook 1963, 1978, 1980; Lunde 1970; Merchant 1951, 1953; Wilson 1965; Micheletti 1976; Arosvski 1983].

1.4.1.6 Analysis of wear particles on the chips

It is well known that most of the wear particles of cutting tools are carried away by adhering to both side surfaces of the chip in turning. Various methods have been developed for detecting tool wear fragments in the chips without using radioactive implants. One method finds the amount of tool wear by chemical analysis [Uehara

1973; 1974]. This method consists of separating wear particles from the chips by pickling and filtering (0.1 μm filter). Electrochemical processes are then used to detect a derivative of tungsten in solution. Because it includes a filtering process, the method would be effective for tool wear detection with relatively large wear particles and may not be suitable for short time tool life testing. Tool wear can also be detected by scanning chips with an electron microprobe analyser [Ham and Schmidt 1968; Uehara 1972]. In this technique, electron beams are used to excite a sample of wear and cutting debris so that X-rays are emitted. These X-rays are subsequently collected and analysed by X-ray spectrometers. Although this method cannot separate flank wear and crater wear, experimental results have shown that it is a good particle concentration detection technique.

1.4.2 Indirect methods for measuring tool wear

Indirect methods of wear measurement involve the correlation of wear with process variables such as cutting force, temperature, power, vibration and sound (acoustic emission). Few reliable indirect methods have been established for industrial use, mainly because of the uncertainty in the correlation between the process parameters and tool wear. Another important limitation which is inherent to most of these methods is that, nearly all of the equations or algorithms suggested to relate a process signal to tool condition are specific to a certain set of cutting conditions [Constantinides and Bennett 1987]. In addition, extensive and expensive wear tests must be carried out for the conditions or set of conditions desired in order to obtain the various constants or parameters needed to predict the tool wear level [Shumsherudin and Lawrence 1984].

1.4.2.1 Cutting forces measurement

One of the most commonly used technique for detecting tool failure is based on measuring the cutting forces. When the measured force exceeds a limit which was predetermined or learned during previous cuts, the tool is assumed to have failed due to excessive wear or breakage [Tonshoff and Wulfsberg 1988; Moriwaki 1984].

In any machining operation three types of forces are usually considered, namely, the cutting velocity force, the feed force and the radial force. To measure the three forces, a dynamometer and other measuring equipment are attached to the machine tool and the tool holder. At the beginning of cutting (at zero time), the cutting force shown on the measuring indicator connected to the dynamometer is noted without any tool wear when using a given set of cutting data. The feed and radial forces are also obtained. After a specific period of time, the new cutting force is recorded and calculated. Mackinnon et al. (1986) stated that for each 0.1 mm width of wear land the cutting force increased by 10%, the feed force increased by 25% and the radial force increased by 30%. Various mathematical expressions have been established for relating the incremented force to the applied force and the depth of nose wear [Colwell 1971, 1974; De Filippi 1969, 1972; Koing 1973; Micheletti 1968; McAdams 1961; Elbestawi 1991; Langhammer 1976; Uehara 1979; Lister 1986; Peklenik 1973; Sata 1974; Takeyama 1970].

A force transducer was developed to measure the dynamic forces from the chip formation process [Lindstrom and Lindberg 1983]. This sensor uses a piezo electric element which, when dynamically compressed, produces an electric output which is proportional to the dynamic forces transmitted through it. Extensive cutting tests have shown that it can be used to indicate flank wear. Other experimental work [Tlusty and Andrews 1983] has confirmed the inter-relationship of the three components of the cutting forces (tangential force, feed force and the radial force). As the tool continues to wear, the forces start to change from their original values. These force variations could be used to identify rapid tool wear and breakage and cease the feed motion before a broken tool starts to scratch the workpiece surface.

A method has been developed for monitoring single crystal diamond tool wear in ultra precision turning operations using dynamic cutting force information and a fuzzy pattern recognition method [Emel and Kannatey 1988]. Some researchers have used the static cutting force and the cutting forces ratio method [Mackinnon 1986] to detect tool wear and breakage. Critics suggest that the reliability of such methods can not satisfy the production process [Yingxue 1988]. However, Ravindra and Srinivasa (1993), found that in turning operations the ratio between force components is a better indicator of the wear process than the estimate obtained using absolute values of the forces.

Damodarasamy and Raman (1993), stated that as a result of their experimental results, they found that the main component of the cutting force exhibits random variations and that with some coated carbides there is very little variation in cutting forces with tool wear. This proves that effective tool condition monitoring might be difficult by using only the cutting forces method.

Micheletti et al. (1968) conducted cutting tests with artificial wear land (few tests with crater wear only and few tests with flank wear alone) and concluded that it was impossible to give accurate information on wear by measuring forces since the cutting force increased with the increase in flank wear and decreased with the increase in crater wear. However, present day tools (carbide and ceramic tools) wear out mostly by flank wear with little or no crater wear. Also, in most industrial applications, crater wear is avoided through the proper selection of insert grade and machining conditions [Powell 1985].

1.4.2.2 Acoustic emission (AE)

AE can be defined as the transient elastic energy spontaneously released in material undergoing deformation, fracture or both [Kannatey-Asibu 1982]. AE has been used to accomplish many purposes in machining processes. An area where acoustic emission has been widely used is the on-line monitoring the tool wear and the detection of tool fracture [Metha 1983; Diei 1987; Iwata 1976; Kulijanic 1992; Teti 1989; Jaing 1987]. The acoustic emission technique utilises a piezoelectric transducer which is attached to a tool holder. The transducer picks up signals which are acoustic emission resulting from the stress waves generated during cutting. Experimental studies have shown that the acoustic emission increases with increasing wear.

The flank wear of a cutting tool can be measured by monitoring the gradual increase of the AE signal level [Inasaki 1981]. The amplitude level of AE increases almost in proportion to the cutting speed during cutting carbon steels and depends strongly on the tool flank wear, while hardly affected by the feed and depth of cut. It was concluded that the signals increased in amplitude at frequencies of about 120, 170 and 210 kHz with an increase in the flank wear land. AE spectral analysis was shown to be a poor diagnostic method for single point cutting tools where marked signal periodicity was absent [Citti 1987]. AE measurements performed at the end of a tool shank proved that AE signals were hardly affected by ambient vibration and noise [Iwata 1976]. Averaged frequency spectra of AE signals were measured at different stages of tool wear. When tool wear increased, the frequency spectrum also increased as a whole, but tended to saturate with further increase of tool wear. It was concluded that the total count of AE had good correlation with flank wear and could be used as an index for in-process tool wear sensing. AE signals with large amplitude were observed when tool cracking, chipping and fracture took place during interrupted cutting on a NC lathe [Okushima 1980]. The tool failures encountered at relatively early cycles of interrupted cutting were successfully detected by monitoring the AE signal, and the feed of the NC lathe was automatically stopped. AE sensing techniques appear to have a quick response time and are more sensitive to tool fracture than force measurements [Lan 1984] and tool variation analysis [Martin 1986], although no experimental evidence of this relative sensitivity is available.

The correlation between AE signals and wear rate has not been firmly established [Mastuoka 1993; Weller 1969; Kannatey-Asibu 1981; Bulm 1990; Moriwaki 1990]. Since all loop elements and signals are interconnected, a change in one parameter influences all signals. Thus, tool wear influences cutting forces, vibration and noise emission. Each signal theoretically contains contributions from all machining parameters. In practice, however, it is difficult to determine which signal is the most representative for a given application.

Recently, approaches for integrating multiple sensors to solve the tool wear sensing problem have been presented by several researchers [Dornfeld 1990; Chryssolouris 1988]. In their work, several indirect tool wear sensing techniques have been integrated, usually using a neural network-based system. Even though these methods provide a systematic approach for sensor integration, the need for extensive training of the neural networks is still a drawback.

While previous work produced significant results, considering that monitoring of tool wear is not a trivial task, it points to at least two important concerns when designing a reliable tool-wear monitoring system. Firstly, the information required to make reliable decisions on tool condition may simply not be available from a single sensor. To improve the quality of information obtained from sensor-based monitoring systems combinations of sensors must be employed to provide corroborative information on the state of the tool condition. The second concern is the interpretation of the sensor's signals to allow timely decision making in real time manufacturing applications. The rapid analysis of rich information from different sensors becomes more crucial for the success of a tool wear monitoring system. For example, the main possible sources of AE signals are:

- Friction contact between the tool flank face and the workpiece resulting in flank wear.
- Friction contact between the tool rake face and the chip resulting in crater wear.
- Plastic deformation in the workpiece.
- Plastic deformation in the chip.
- Collision between the chip and tool or tool holder.
- Crack formation in the chip (chipbreakage).
- Tool edge chipping.

There is a wide spectrum of commercial sensors for measuring cutting force, power, vibration etc. [Gautschi 1971; Micheletti 1976]. Numerous sensors have also been developed for particular applications [Hoffman 1987; Machinnon 1983]. The majority of available sensors change their static and dynamic characteristics in response to the change in their working environment. Periodic tuning is needed to match the expected characteristics of their working environment. In addition, the relationships between the output signals and the cutting noise (force, power, vibration etc.) has not been fully defined and a large number of tests are needed to estimate the constants and parameters that relate the output signals to the cutting noise.

1.4.2.3 Sound

Sound from a machining operation measured near the cutting zone has been used to monitor the condition of cutting tools. Low frequency noise spectra resulting from the rubbing action of the tool and the workpiece were used to monitor tool flank wear [Sadat and Raman 1987]. The increase in the noise level was significant during the initial stages of tool wear and then tended to saturate. The noise level decreases with increasing cutting velocity. This is explained by the decrease in the friction at the tool workpiece interface that results from an increase in temperatures as the cutting velocity increases. Machining noise exhibits a characteristic frequency at around 4 to 6 kHz for a large variety of workpiece material and operating conditions [Lee 1986]. The sound pressure level (SPL) at this characteristic frequency showed good correlation with tool wear. SPL dropped off before the rapid increase in the maximum flank wear which indicated that the operation was about to enter the third region of the wear zone as shown in Figure 1.5.

1.4.2.4 Vibration

In metal cutting, the workpiece and chips rub against the tool and produce vibration which can be used for tool failure monitoring. A data dependent system using a discrete modelling method [Pandit 1978] was used for measuring tool wear. A strategy for on-line tool wear sensing and automatic detection of critical tool wear was developed to facilitate computer controlled optimal tool replacement [Pandit 1982, 1983].

A worn tool detector was constructed using a vibration transducer mounted on the tool block of the machine tool [Weller 1969]. It was found that the total amount of vibration energy in the frequency range of 4 to 8 kHz increased, as the length of the cutting edge wear land increased. It was also found that the vertical tool vibrations in the course of stable machining were almost sinusoidal, with the frequency being equal to its natural frequency [Martin 1974]. The power acceleration signal obtained by spectral analysis was a linear function of the cutting velocity and tool wear and varied in the ratio of 1:10 between a new and a worn tool.

1.4.2.5 Variation of power input

The electrical power input rise with the increase in the wear land of the tool. The measurement of power input is less sensitive than force measurement and it is easier to implement [Martin 1986]. A power monitor device can be connected to the machine tool to execute measurements of the electrical power required to drive the spindle motor. This device measures the current, voltage and power factor of the spindle motor and computes the power consumption at any instant. The actual cutting power can then be obtained by subtracting the idle power of the spindle from the total power. The accuracy and reliability of the method rely on both the response characteristics of the monitoring device and the procedure implemented to calculate the net cutting power. One such current measurement system was found to be effective in preventing tool breakage at medium and heavy cuts [Novak 1986].

1.4.2.6 Cutting temperature measurement

It has been suggested that two different breakdown mechanisms are associated with wear of cemented carbide tools during turning. The flank wear is thought to be the result of an abrasion wear process requiring a hard, strong tool material to offer resistance. On the other hand crater wear is thought to be controlled by diffusion of compounds from the tool material into the workpiece and their subsequent removal by the swarf. Diffusion is temperature controlled and, therefore, the cutting temperature can be used to monitor tool failure by crater wear. Cemented carbide, cubic born nitride (CBN) and HSS tools fail by crater formation on the rake-face at high cutting speeds. The crater wear is due to chemical instability of the tool material and does not depend on the hardness of the tool once the hardness exceeds about 4.5 times the workpiece hardness [Suh 1977]. This is the reason why even very hard materials such as CBN and diamond tools, wear when cutting steel. The crater wear rate of cemented carbide and HSS tools can be decreased by applying a 5 μm thick coating of carbides, nitrides or oxides that are more chemically stable than the substrate material [Naik and Suh 1975].

Numerous investigations have been made to predict tool wear by monitoring the change in temperature in the cutting zone [Beadle 1971; Groover 1971; Jaeschke 1967; Olberts 1959]. It was found that approximately 60% of heat generated at the work-tool interface was conducted into the workpiece and the remaining 40% was removed by the chip [Boothroyd 1967]. The mean temperature taken over the tool wearing surfaces (both the face and the flank) increased with increasing length of the flank wear land. Temperature measurements have also been used with an analytical model for tool wear monitoring [Turkovich and Kramer 1986; Colwell 1979]. An algorithm that predicted the wear rates of hard coatings throughout the velocity range of high speed steels and cemented tungsten carbides was developed. The reliability of work-tool thermocouple methods was reported to be affected by the material properties at the junction since the thermal voltage signal was sensitive to cutting conditions [Zakaria 1975]. Another thermocouple based approach has been used in tool wear monitoring [Groover 1977; Levy 1976; Solaja 1973]. An embedded thermocouple is located at a position on the cutting tool remote from the cutting edge. Experimental results showed a linear relationship between thermocouple output and tool wear area [Groover 1977].

1.4.2.7 Surface roughness measurement

It is well known that the surface roughness of the workpiece is influenced by the condition of the cutting tool. This phenomenon has been utilized for tool condition monitoring. A fibre-optic transducer was used for in-process measurement of surface roughness during finish turning machining [Spirgeon and Slater 1974]. The transducer was used to trace the same path as a cutting tool and the method was based on the principle that the reflectivity of light from a newly turned surface varies inversely proportional to the roughness of that surface. By applying a pair of optical reflection systems, surface roughness can be effectively measured up to approximately 40 μm of maximum surface roughness [Takeyama and Sekiguchi 1976]. This method was claimed to be very effective in detecting the slightest change in the condition of the cutting edge in an on-line manner.

1.5 ANALYTICAL MODELS FOR TOOL LIFE PREDICTION

There are several input parameters to the cutting process such as the cutting velocity, feed rate, depth of cut, tool and workpiece material properties, and cutting fluid. The output parameters include the cutting temperature, chip thickness, cutting forces, surface finish, and tool wear. Most of the input parameters listed, except material properties, can be measured on-line, directly or indirectly, depending on the type of the machining process. Likewise, most of the output parameters are measurable to a certain degree. General studies of the wear phenomena have been completed and there is general agreement that the wear process is a stochastic phenomenon and can be modelled by probabilistic models [Boothroyd 1989; Suh 1980; Billatos 1986]. Tool wear modelling and control can be either predictive (off-line) or real-time (on-line).

Off-line, non-sensorial prediction and monitoring can be done using computer-based process models which utilize feedback information from the machining process [Maropoulos 1995]. The feedback can be collected manually by the operator/planner, and it can either be a qualitative description of problems noted by observing the process or the result of subsequent quality inspection tests. On-line monitoring and control makes use of multiple sensors, which are typically used for measuring spindle current, cutting forces, vibration and acoustic emission as described earlier.

The maximum machining ratio (*MR*), which is the ratio of the volume of material removed to the volume of tool wear, is proposed by Singh and Khare (1983), for the assessment of tool life. For a given condition, the *MR* is given by:

$$MR = \frac{v\,s\,a\,t}{V_w} = \frac{v\,s\,a\,\rho}{W}$$

where; v is the cutting velocity, s the feed rate, a the depth of cut, t the cutting time, ρ the density of the tool material, V_w the volume of tool wear and W is the weight of tool wear. Thus, when the weight of tool wear at any time is known, the *MR* can be calculated under various cutting conditions. Rao and Lal (1977), found that the machining ratio increases with cutting time to a maximum and then decreases and that the maximum *MR* corresponds to the inflection point on the flank wear growth curve (Figure 1.5). The tool wear can be determined by direct weighing before and after use or by indirect measurements using radioisotopes [Wilson and McHenry 1965]. In the measurement of tool wear, dust, foreign particles and built-up edge adhered to the tool are also weighed. Thus, tool cleaning is necessary before weighing. A built-up edge on a carbide tool can be dissolved in nitric acid, leaving the surface unaffected [Trent 1959]. This method of cleaning is not applicable to high speed steel tools. As tool wear is small, a highly sensitive balance is required for accurate weight measurement. The tool wear weight (volume) can also be calculated by using a mathematical model.

Uehara 1975, proposed a model that defined the wear volume as a sum of the flank wear volume and crater wear volume:

$$V_w = \frac{1}{2} V_B^2 L \tan\gamma + \frac{2}{3} \mu W KT$$

where; V_B and L are the width and length of the wear land, γ is the clearance angle and μ, W and KT are the width, breadth and maximum depth of the crater wear respectively. The maximum *MR* appears to be a useful criterion for roughing operations since it gives the maximum tool life, as the tool can be used until the critical point on the flank wear is reached. However, this criterion is not suitable for finishing operations.

A sensing device was developed to measure tool wear indirectly by monitoring the change of the workpiece diameter during turning operations [El Gomayel and Bregger 1986]. The change in the diameter is sensed by electromagnetic sensors which gives a voltage output directly related to the gap between the sensor and the workpiece. The voltage output varies with the change in the distance between the probe and the workpiece because of the variation in the magnetic field. A minute change in the diameter of the workpiece is an indication of the wear on the cutting tool. The workpiece diameter (D) is given by :

$$D = L - (\Delta x_1 + \Delta x_2)$$

where; L is the total length between the two sensors, Δx_1 and Δx_2 are the gaps between $sensor_1$ and $sensor_2$ respectively. The total voltage output v_{total} is given by:

$$v_{total} = v_1 + v_2 \cong -k\,(\Delta x_1 + \Delta x_2)$$

where; v_1, v_2 is the voltage in $sensor_1$ and $sensor_2$ respectively, and $k = -v_1 / \Delta x_1$.

In a model proposed by Billatos and others (1986), the wear process is limited to two regions: nose wear and flank wear. In this model, the cutting edge is assumed to be triangular in cross section and the nose wear was described as the distance W_n of the worn edge from the original position of the edge when new. The predictive equation for tool wear W at any time t is:

$$W(t) = a_o + a_1\, t^{1/2} + a_2\, t^{3/2}$$

where; a_o , a_1 and a_2 are constants depending on the tool material and cutting conditions and which can be determined experimentally. Tool life can be determined at any specific level of expected wear by obtaining the cutting time associated with that level from the cumulative tool wear. This means that a large number of tests are needed. Also, some tests show that there was virtually no flank wear. Hence more work is needed to define the effect of flank wear on the model coefficients.

The mechanical behaviour of WC-Co composites can be divided into three temperature domains. WC-Co is brittle below 500 °C, tough between 500 and 800 °C and shows plastic deformation above 800 °C. Once the tool temperature has been related to the cutting velocity, the life of WC-Co cutting tools can be predicted based on the mechanical behaviour of WC-Co as a bulk material. A model was presented [Mari and Gonseth 1993] to explain the observed behaviour of tool life versus velocity curves for continuous cutting. An assumption was made that there is a direct relationship between E_{mech} (the mechanical energy related to the deterioration of the cutting geometry) and the wear of the tool. This model defines the Taylor curve as representing the plot of the cutting velocity versus the time T required for the cutting tool to receive a critical energy E_c to obtain a given plastic deformation (i.e. the flank wear V_B).

$$T = \frac{E_c}{\alpha v + \beta e^{-Q/K\theta}}$$

where; α is a constant related to the frictional force, v is the cutting velocity, β is the proportionality coefficient, Q is the activation energy, K is the Boltzmann constant and θ is the temperature proportional to cutting velocity.

At high cutting velocity, the thermal stress exceeds the yield stress of the material and becomes the dominant factor of wear since the temperature of the material is high enough for plastic deformation to take place. This model gives a good description of the high velocity-high temperature region but cannot explain some types of failure such as comb cracking, which is an important wear mechanism during interrupted cutting. Comb cracking usually appears on the rake face of the cutting tool, perpendicular to the cutting edge. There are two arguments that suggest that comb cracks are due to thermal fatigue. Firstly, comb cracks appears only in interrupted cutting, where there is a cycle of heating and cooling. Secondly, cracks caused by mechanical stress should be parallel to the cutting edge. Instead, comb cracks are perpendicular to the cutting edge and cannot be attributed to mechanical stress during machining. In conclusion, the thermal model gave good results in continuous operations rather than interrupted cutting.

An indirect method based on the relationship between flank wear and cutting power in turning operations was described by Cuppini (1990). Let P_c be the net cutting power, P_t the total power measured during the cut and P_i the power due to the idle running spindle:

$$P_c = P_t - P_i$$

P_t can be measured at any instant. The relationship between P_i and spindle speed (N) is strongly influenced by the temperature at which the machine tool is operated. Up to 50% of the variation in P_i can depend on the operating temperature. Such a variation may mask the variation in P_c due to tool decay.

Ravindra 1993, proposes the development of a mathematical model to describe the wear-time and wear-force relationships for turning operations. Material properties and tool edge geometry variation have been identified as major noise sources in signals measured during machining. It was observed that, although random variations were present in force ratios, they were smaller compared with the overall increase in the values.

A model was developed [Damodarasamy and Raman 1993], based on pattern recognition that combines the direct output of the feed force, radial force and the root mean square (r.m.s) value of the AE signal to model the flank wear states in machining. In this model, the main cutting force is omitted from the pattern vector together with vibration and temperature. Further, the rate of success of pattern-training is defined as the ratio of the number of patterns correctly classified to the total number of patterns. The success rate is 100% if the weight vector classified all the pattern correctly. In this model's results the success rate for various tests varied between 39.57% to 100% and the success rate in classifying signal from the two actual tests were 75.44% and 48.5%. Therefore, more tests must be performed to ensure the validity of the methodology.

A mathematical expression was established by Sewailem (1980) to relate the incremental force to the applied force and to the maximum depth of nose wear. The gradual increase of the cutting force was given by:

$$F_c = F_w + \Delta F$$

where; F_c is the vertical cutting force and F_w is the initial force. The increment ΔF of the cutting force was used as criterion of nose wear.

Nagasaka and Hashimoto (1982) proposed a new tool life equation for modelling tool wear. In this equation the cutting conditions and the amount of tool wear were treated as independent variables. The relationship between the flank wear (V_B) and the cutting time t was given by:

$$t = T_o \exp \{ -\exp(b)\, V_B^{\,n} \} \qquad n < 0$$

where; b and n are constants and T_o is the critical cutting time. T_o is a function of cutting conditions and is given by:

$$T_o = a\, v^{n1}\, s^{n2}$$

where; a, $n1$ and $n2$ are constants, v is the cutting velocity and s is the feed rate. The tool life equation becomes;

$$t = a\, v^{n1}\, s^{n2} \exp \{ -\exp(b)\, V_B^{\,n} \}$$

Another model presented by Teshima and others (1993) is based on a neural network to estimate the tool life and wear type of cutting tools from their image data and cutting conditions in turning. The inputs to the system are:

- The state of a cutting tool, including crater wear and flank wear, obtained as image data.
- The cutting conditions.

This network had an input layer of 235 processing elements (dealing with tool image data and cutting conditions), one hidden layer of 65 processing elements and one output layer of 6 processing elements (giving data about the remaining life of finish cutting tools, medium-finish cutting tools, rough cutting tools, flank wear, crater wear and groove wear). The signal of the k^{th} processing element Q_k (remaining of tool life) in the output layer of the neural network was determined by the two following steps:

- The first step is to produce the output signal H_j in the hidden layer by computing the weighted sum of the input signal I_i:

$$H_i = f\left(\sum_{i=1}^{235} w_{ji}\,(I_i + \theta_j)\right)$$

where; w_{ji} is the weight on the connection from the i^{th} processing element in the input layer to the j^{th} processing element in the hidden layer, θ_j is threshold of the j^{th} processing element in the hidden layer and f is the activation function.

- The second step was to calculate the output signal Q_k in the output layer from the signal H_j in the hidden layer.

$$Q_k = f\left(\sum_{j=1}^{65} V_{kj}\, H_j\, \gamma_k\right)$$

where; V_{kj} is the weight on the connection from the j^{th} processing element in the hidden layer to the k^{th} processing element in the output layer and γ_k is the threshold of the k^{th} processing element in the output layer. By adjusting the connection weights and thresholds of the above two equations, the neural network can predict the remaining life and the wear type of cutting tools.

1.6 AIMS AND OBJECTIVES OF PRESENT WORK

The main aim of the research described herein is to define and develop a predictive, off-line tool life prediction, control and management system. The initial operation of the system is based on theoretical tool life values derived by processing information from tool manufacturer's catalogues. The results are moderated by collecting and processing tool life feedback information, obtained by periodic direct measurement of tool wear using optical methods like the toolmaker's microscope. The methods and the computer system were developed according to the following objectives:

- To work within tool selection and management. Tool life control must be a part of the process planning activity to achieve optimal cutting data and tool replacement strategy.

- To ensure data driven operation. The quality of tool life predictions is influenced by the collection and processing of tool life data from real processes.

- To achieve reduced dependency on special sensors. This is in order to reduce cost and avoid complexity of sensor reliability and signal interpretation.

- To provide a quick, real time tool life prediction method. Efficient processing of data is achieved by using database functions, multiple regression, least-squares method and efficient metal cutting algorithms.

- To be an easily implemented method. Initial operation is based on catalogue data and can be implemented directly.

- To be industrially applicable rather than laboratory based. The input data required as well as the data required to maintain the model are readily available to machinists.

OVERALL STRUCTURE OF TLC

TLC is part of the intelligent tool selection (ITS) system which is under development at Durham University. ITS selects tools and calculates the optimum cutting conditions for the selected turning tools. The initial testing of ITS in the laboratory gave encouraging results [Maropoulos and Alamin 1995]. The optimum cutting data result in a specific tool life for any work material, carbide grade and type of cut combination.

The specific objectives of the work presented herein is to define, develop and experimentally verify an interactive and user-friendly system to assist the process planner in the prediction, control and management of tool life, in the context of a tool selection system for turning and boring operations. The tool life control system (TLC) is a rule-based system and uses the extended Taylor's tool life equation to predict the amount of wear on a cutting tool. The initial constants for calculating tool life are derived from tool manufacturers' data using multiple regression methods. A series of experimental tests should be completed and the flank wear must be measured to find the real tool life of coated carbide tools for different cutting conditions. The collection of tool life data allows the re-calculation of the exponents of Taylor's equation which may be different from the initial values. The corrected equation is used to assess and modify the initial tool life values predicted by the system and improves the feasibility of implementing such a system in industry.

The overall structure of the tool life control system is shown in Figure 2.1. TLC is PC based and has been implemented using the expert system shell *Crystal (version 4.5)* for coding the rule based logic and *dBaseIV* for constructing and managing the databases.

Crystal is an expert system shell that allows the creation of knowledge bases consisting of a set of linked *"if-then"* rules. *Crystal* processes the rules using backward chaining until an alternative of the master rule is proved true. A typical expert system asks the user a series of questions, which can be answered in a *yes/no* fashion, by selecting from menus or by typing-in data. Questions and results are presented back to the user, according to the conclusions derived by inferencing on the rules. The *Crystal* based system has a friendly user interface to allow easy execution of the program. Queries are automatically displayed on the screen and warning messages are displayed to prompt the user whenever incomplete or incorrect data has been given.

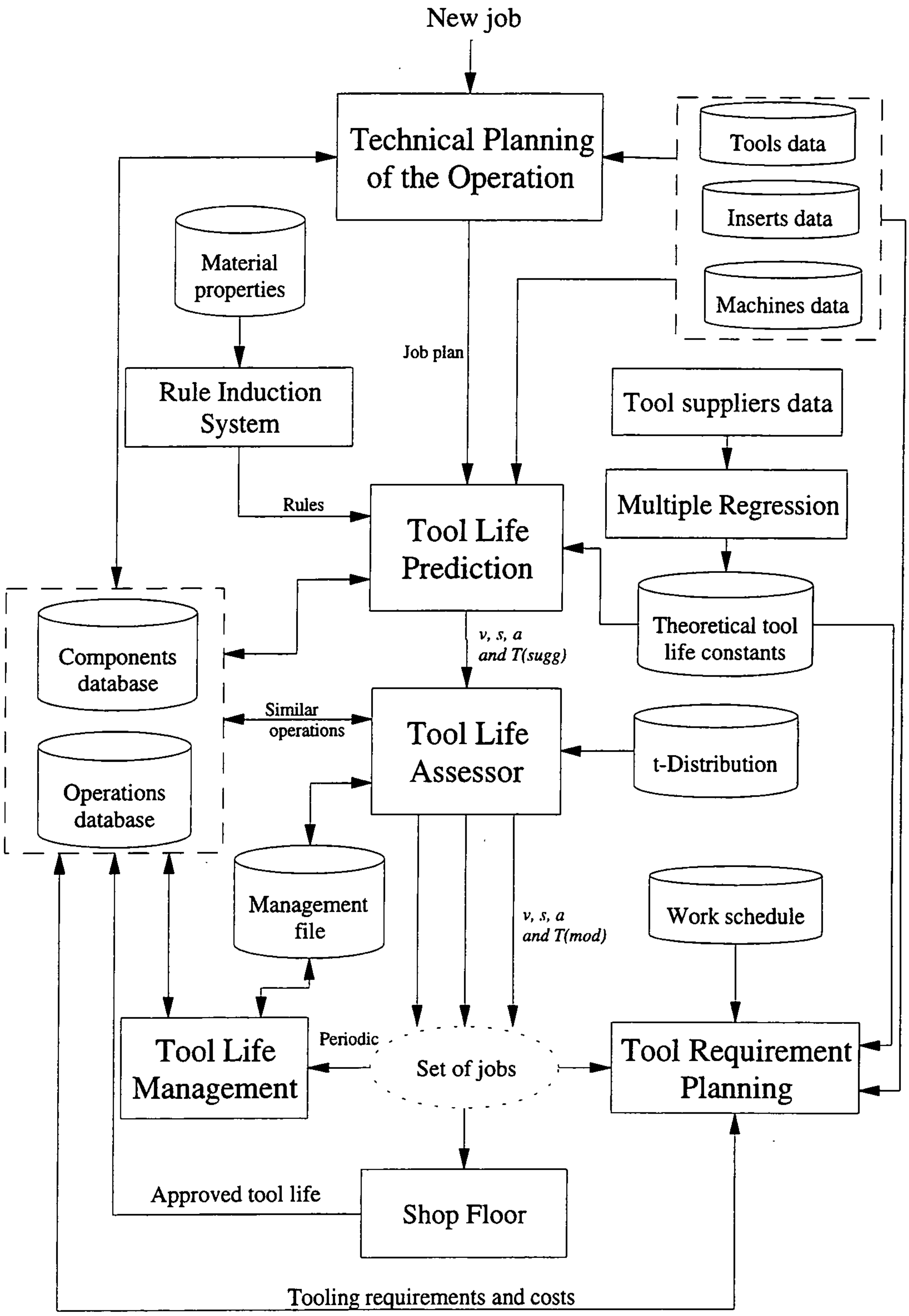

Figure 2.1 Overall Structure of Tool Life Control system (TLC)

TLC can be applied to today's manufacturing environment in two ways. It can be used as a stand-alone system, that is, it can be consulted directly and independently by the user without any other system interface. The user simply selects the combination of material, carbide grade and type of cut and the tool life value will be calculated and displayed on the screen. Alternatively, the system can be run as an integral part of ITS. For example, the components and operations database shown in Figure 2.1 are initially created by running ITS and are shared between ITS and TLC. TLC accepts the output of ITS as its input and the user may modify this data before it is processed. The tool life control system (TLC) has five main functions:

- For each turning, facing or boring operation, the technical planning of the operation module (TPO) selects tools that can satisfy the basic geometrical constraints of an operation and calculates efficient cutting conditions (suggested cutting conditions) by taking into account a number of machining process constraints such as power and cutting forces.
- For a selected operation, the tool life prediction module (TLP) calculates the initial tool life value (T_{sugg}) on the basis of the suggested cutting data. The calculation of tool life is based on theoretical tool life constants which are derived from tool manufacturer's data.
- Based on approved (real) tool life values for similar operations (at least four points), the tool life assessor module (TLA) generates a dynamic multiple regression to calculate the approved tool life coefficients ($\ln C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$). A modified tool life value (T_{mod}), is calculated for the selected operation using the new calculated

coefficients. The initial (T_{sugg}) and modified (T_{mod}) tool life values are stored in the operations file and the modified value is used on the shop floor. The final tool life obtained is referred to as approved (T_{app}) and is collected from the shop floor.

- For a given material, carbide grade and type of cut (i.e., finishing, medium-roughing or roughing), the tool life management module (TLM) retrieves all the available tool life data from the system's database (operations database). For each operation TLM retrieves three tool life values namely, the initial suggested value (T_{sugg}) from TLP, the modified value (T_{mod}) and its confidence limits from TLA, and the approved value (T_{app}) collected from the shop floor. TLM also retrieves the calculated tool life coefficients (the theoretical coefficients from the theoretical tool life constants database and the approved coefficients calculated by TLA). TLM analyses the above retrieved data in order to assess the accuracy of tool life predictions and confirm the stabilisation of approved data. This module can run once every two to three months or when approved data becomes available.
- The tool requirement planning module (TRP) addresses the problem of controlling and balancing the wear rate of the selected tools. Tool wear balancing refers to the modification of the wear rate of the tool's cutting edge by the appropriate alteration of machining parameters [Maropoulos 1989]. Using this method, one can balance the wear rate of several tools so that each tool will machine a certain number of parts that optimize the overall tool changing strategy. Finally, the complete requirement of consumable inserts is computed for a given period of the shop floor scheduling system.

2.1 SYSTEM'S DATABASE REQUIREMENTS

The tool life control system (TLC) has access to ten databases as shown in Figure 2.1. Six of these databases are "static" since they are not updated as a result of running the system. The structures of the static databases are as follows:

- ***Tools database***
    - Tool code.
    - External or internal tool.
    - Tool capability (longitudinal, profiling or facing).
    - Tool cost.
    - Approach angle.
    - Trailing angle.
    - Hand side (i.e. right-left or left-right).

- ***Inserts database***
    - Insert code.
    - Insert cost.
    - Number of cutting edges.
    - Nose radius.
    - Length of the cutting edge.
    - Carbide grade, such as TP10.
    - Chipbreaker limits (maximum and minimum feed rate and depth of cut).

- ***Machine tools database***
    - Machine code such as CNC-1000.
    - Machine Power.
    - Speed range.
    - Machine clamping force.
    - Cost rate of the machine tool.
    - Worn tool changing time.

- ***Material properties database***
    - Material classes.
    - Material sub-classes.
    - Chemical composition (%).
    - Brinell hardness (HB).

- ***t - Distribution database***

There is a different *t* distribution for each sample size. A particular *t* distribution is specified by giving the degrees of freedom. The density curves of the sample distributions are in the shape of the standard normal curve. That is, they are symmetric about 0 and are bell-shaped. The spread of the *t* distributions is greater than that of the standard normal distributions. The *t* distribution has more probability in the tails and less in the centre when compared to standard normal distributions. *Appendix 1*, gives upper *p* critical values for the *t* distributions [Moore and McCabe 1993].

- Degree of freedom.
- x-critical value (95 %).

- ***Tool life constants database***
  - Carbide grade (i.e., P20).
  - Workpiece material sub-class (i.e., free cutting steel), 32 sub-classes in total.
  - Type of cut (finishing, medium roughing or roughing).
  - Theoretical tool life coefficients ($ln\,C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$) calculated by TLP using tool manufacturer's data.
  - v_{max} and v_{min} is the maximum and minimum velocities recommended by the tool manufacturers to cut a specific material sub-class.

The seventh, eighth, ninth and tenth databases are "dynamic" because they are updated as a result of running the system and they are the most important source of approved information since they contain the following information:

- ***Components database***
  - Component code.
  - Material sub-class.
  - Number of cutting operations (up to five operations for each component).

- ***Operations database***

General description:

- Machine code.
- Type of the sub-operation (i.e. right-left).
- Type of cut (finishing, medium roughing or roughing).
- Tolerance or surface finish.
- Cutting fluid.

Geometrical data:

- Maximum approach angle of the profile (K).
- Maximum trailing angle of the profile (Ψ).
- Total depth of cut (a_{stock}).
- Cutting point distance (*cpdist*).
- Clamping length inside the chuck (*clmlen*).
- Clamping diameter (*clmdia*).
- Cutting point diameter (*cpdia*)
- If hollow: the maximum internal diameter (D_{int}).
- External diameter (D_{ext}).
- Length to diameter ratio (*L/D*).

Tool and cutting data:

- ISO code for holder/boring bar.
- ISO code for insert.
- Insert grade.

- Type of operation (longitudinal, profiling or facing).
- External or internal cut.
- Approved cutting conditions (v , s , a) from the shop floor.
- Suggested cutting conditions (v_{sugg} , s_{sugg} , a_{sugg}) from TPO.
- Suggested tool life value (T_{sugg}) from TLP.
- Modified tool life value (T_{mod}) and its 95% confidence calculated by TLA.
- Approved tool life value (T_{app}) from the shop floor.
- Number of passes (n_{passes}).

- ***Management file database***
  - Material sub-class.
  - Insert carbide grade.
  - Type of cut.
  - Approved tool life coefficients ($ln\,C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$) calculated by TLA.
  - Variation in the lnC parameter.
  - Variation in the $\frac{1}{\alpha}$ parameter.
  - Variation in the $\frac{1}{\beta}$ parameter.

- ***Production schedule database***
  - Week number.
  - Day number.

- Machine code such as CNC-1000.
- Component code.
- Number of cutting operations.
- Batch size (q).
- Number of batches (w).

2.2 DATABASE MANAGEMENT FUNCTIONS

This module provides the means for the user to access and modify the existing database files used by the TLC system. Once this module is selected from the top level menu, the system shows the user a list of all the database files. By selecting a specific file, the user is prompted with two options: "Search for a record", or "Edit". The user can search for a specific record, if the search key is known, by selecting "Search for a record" or browse through the records of the file by selecting the "Edit" option.

2.2.1 Search for a record

To search for a known record, the user must enter the identification of the intended record. For instance, when searching for a machine record in the machines file, the system will ask the user to enter the machine code. If the information of this machine already exists in the file, the system automatically switches to the "Edit" screen, showing all the information available about this machine. The "Edit" screen allows the user to either alter the chosen record or add a new record.

2.2.2 Edit a record

At the "Edit" screen, the user is given a list of options shown at the bottom of the screen. These are listed as follows:

- Update: Update the current record.
- First: Go to the first record of the selected file.
- Last: Go to the last record of the selected file.
- Next: Move to the next record.
- Prior: Move one step backward from the current record.
- Add: Add a new record to the end of the selected file.
- Delete: Delete the current record logically by setting a deletion flag.
- Recall: Recall the current record which is deleted logically.
- Pack: Delete the records which have been marked for deletion.

To leave the "Edit" screen, the user must simply select "Quit" to go back to the level where the options "Search for a record", "Edit" and "Quit" are shown. One may select "Quit" again to go back to the main control menu of TLC.

Chapter 3

TECHNICAL PLANING OF THE CUTTING OPERATION

Technical planning of the cutting operation (TPO) is the first function of the system and the first option of the top level menu of TLC. TPO contains a procedure to select tools for turning operations performed on a CNC (computer numerically controlled) turning centre. The turning tools considered herein consist of a holder and an indexable tungsten carbide insert. TPO generates efficient machining conditions (cutting velocity, feed rate, and depth of cut) using several equations derived from metal cutting theory and practical engineering knowledge. TPO incorporates considerations in relation to the component and cutting profile geometry, material sub-class and operation type as well as tool and insert characteristics. The structure of TPO eliminates the need to store a large amount of data for a wide combination of tools, materials and operations.

3.1 SPECIFICATION AND FUNCTIONALITY OF TPO

This module selects tools and generates cutting conditions which can perform the machining operation adequately. The objective is the rapid calculation of initial cutting data. In this process a number of constraints are taken into account such as power and chipbreaking. The cutting conditions may not be optimal, as final tool life is not considered at this stage. The overall structure of the module is shown in Figure 3.1. The functions of TPO are described below.

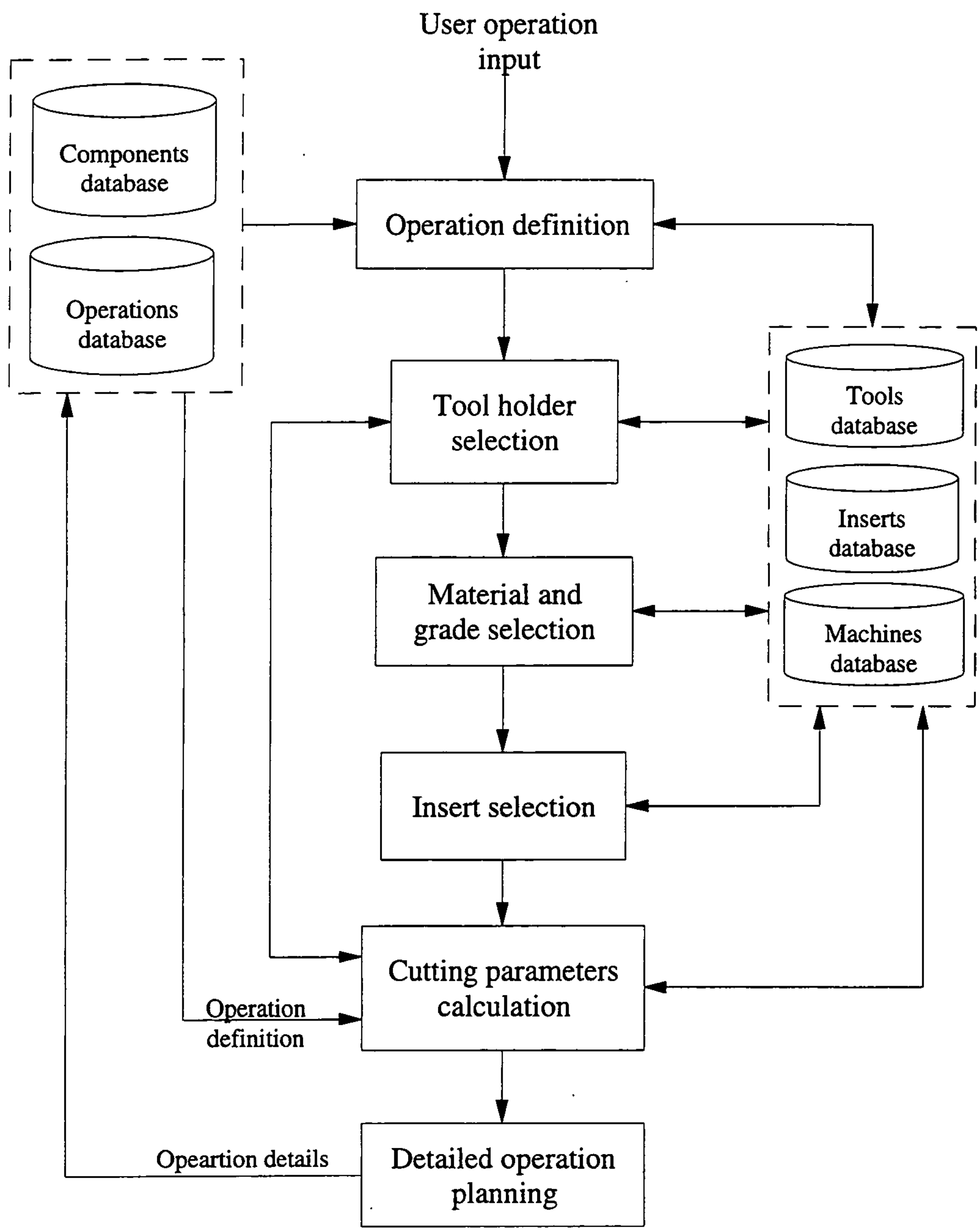

Figure 3.1 The Overall Structure of the Technical Planning Module

3.1.1 Operation definition

Turning and boring are the main types of machining operations that have been implemented. They are divided into external and internal and in each case there can be profile, facing or longitudinal cutting. There is also a need to specify the type of machining: rough cut to remove the bulk of the stock; finish cut, which removes a small amount of material and creates the desired surface finish; and medium-roughing cut for intermediate depths of cut. Usually, the first step is to select an existing operation from the ITS/TLC operations database. The user can modify the information according to the details of the new operation such as its length, diameter and profile geometry. The user can also change the machine tool to be used. The system will display a list of machines from the machines database or the user can add a new machine with its specification such as power and speed range. Clearly, the operation of this function is based on the variant approach to process planning.

3.1.2 Tool holder selection

This function is executed having defined the geometry of the profile to be machined (profile's approach and trailing angles), the type of operation (longitudinal, profiling or facing) and the associated sub-operation (i.e. forward longitudinal turning, facing out, etc.). The sub-operation is only indicative of the general machining direction since, in practice, the tools have to follow the component's profile. However, the type of operation and sub-operation specified serve as a guide for the selection of the type and hand-side of the tool holder (i.e. turning right-hand or left-hand tools). The inferencing continues with the scanning of the tools data file and tools compatible with the operation are extracted. The approach and trailing angles of the tool holders are compared with those of the profile. Tools are selected with angles larger than the profile. Figure 3.2. shows the way these angles are measured for a tool and a profile.

Each operation will have a set of tool holders displayed on the screen and the user is prompted to select one tool.

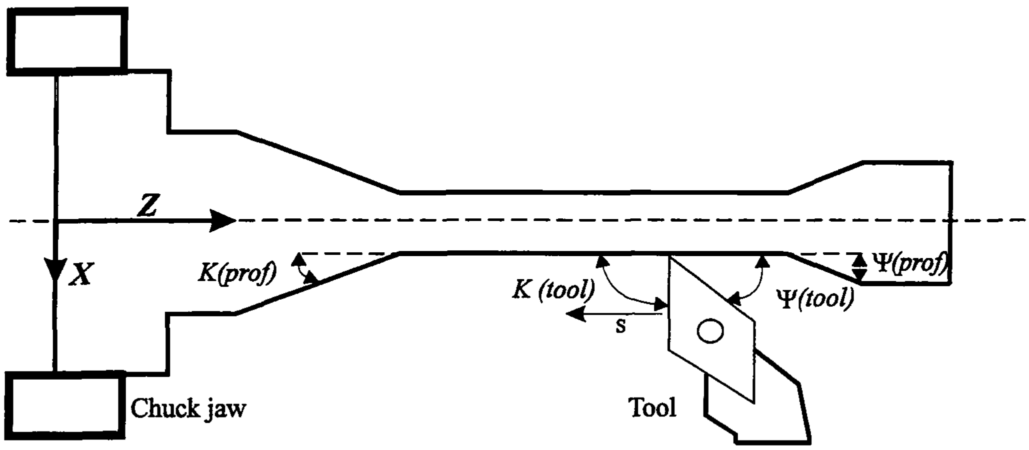

Fig. 3.2 Approach and trailing angles of tools and profiles [Maropoulos and Gill 1995]

3.1.3 Material selection

At this step, the module displays a list of general material classes (seven in total) on the screen and asks the user to select one class of material to be machined. Another list of material sub-classes corresponding to the selected material class is then shown and the user is asked to select one. Overall there are thirty two sub-classes for the seven general material classes as shown in Table 3.1.

3.1.4 Insert selection

Based on the selected material, a list of carbide inserts recommended by tool manufacturers for machining this material is created and displayed. The *ISO* classification of carbide inserts into “P”, “K” and “M” application types is used to select suitable inserts. TPO contains a set of rules relating the application range of each insert with a number of material sub-classes. The second consideration is to eliminate inserts which are not suitable for the selected tool holder. The only realistic way to retrieve an insert which is compatible to the selected tool holder is to match the insert's shape and cutting edge length with those of the tool holder. The *ISO* codes of inserts and holders can be used to automatically check whether an insert can be located on a given holder. In particular, the second character of the holder's code indicates the shape of insert and must be identical with the first character of the insert's code. Also, the last two digits of the holder's code indicate the length of the cutting edge and should match the first two digits found in the insert's code.

Example

Tool holder code: PCLNR2020-12A

Insert code: CNMG120408-MF2

TPO matches the second character (C) and the last two digits (12) from the tool holder code with the first character (C) and the first two digits (12) from the insert code to ensure the same shape and size. Several inserts may be found with a suitable grade and suitable for the selected holder. The user is required to select one from all suitable inserts for final use.

Table 3.1 Material groups for cutting data recommendations

Material classes	Material sub-classes	Hardness Brinell (HB)	K_{sm} (N/mm^2)
Mild and alloy steels	Very soft steel	– 140	1900
	Free cutting steel	140 – 160	2100
	Structure steel	160 – 180	2250
	High carbon steel	180 – 220	2100
	Normal tool steel	220 – 260	2600
	Difficult tool steel	260 – 330	2700
	Hardened steel	330 – 450	4500
Stainless steels	Free cutting stainless steel	150 – 270	2300
	Moderately difficult stainless steel	270 – 300	2300
	Stainless steel difficult to machine	300 – 325	2500
	Duplex stainless steel		2500
Cast iron	Grey cast iron - low hardness	– 180	1100
	Grey cast iron - medium hardness	– 230	1100
	Low alloy cast iron	– 250	1800
	Medium-hard alloy cast iron	– 275	1500
	High alloy cast iron	– 300	1800
Aluminium alloys	Aluminium alloy - wrought	– 100	500
	Aluminium alloy - cast	– 150	750
Heat resistant super alloys	Annealed iron base alloy	200	3000
	Aged iron base alloy	280	3050
	Annealed nickel base alloy	200 – 250	3500
	Aged nickel base alloy	300 – 475	4150
	Cast nickel base alloy	200 – 425	4150
	Annealed cobalt base alloy	180 – 250	3500
	Aged cobalt base alloy	260 – 350	4150
	Cast cobalt base alloy	200 – 450	4150
Titanium alloys	Pure titanium		1530
	α, near α and $\alpha + \beta$ alloys		1675
	$\alpha + \beta$ alloys in aged condition, β alloys in annealed or aged conditions		1690
Bronze - brass alloys	Lead alloy	110	700
	Brass, red brass and bronze alloy	90	750
	Copper and copper alloy	100	1750

3.1.5 Depth of cut and feed rate calculations

3.1.5.1 Finishing operation

- *Depth of cut*

Finish machining is a single pass turning operation. Therefore, TPO will set the total depth of cut (a_{stock}) equal to the depth of cut.

$$a = a_{stock} \tag{3.1}$$

The depth of cut is effectively defined by the geometry of the operation and it must be within the chipbreaker application range (i.e., $a_{c\,min} \leq a \leq a_{c\,max}$) (see Figure 3.3).

If the depth of is cut less than $a_{c\,min}$, the system will set the depth of cut to be equal to the minimum depth ($a = a_{c\,min}$) and if $a > a_{c\,max}$ the depth of cut is set equal to the maximum depth ($a = a_{c\,max}$). If the user does not accept this suggestion another chipbreaker must be selected.

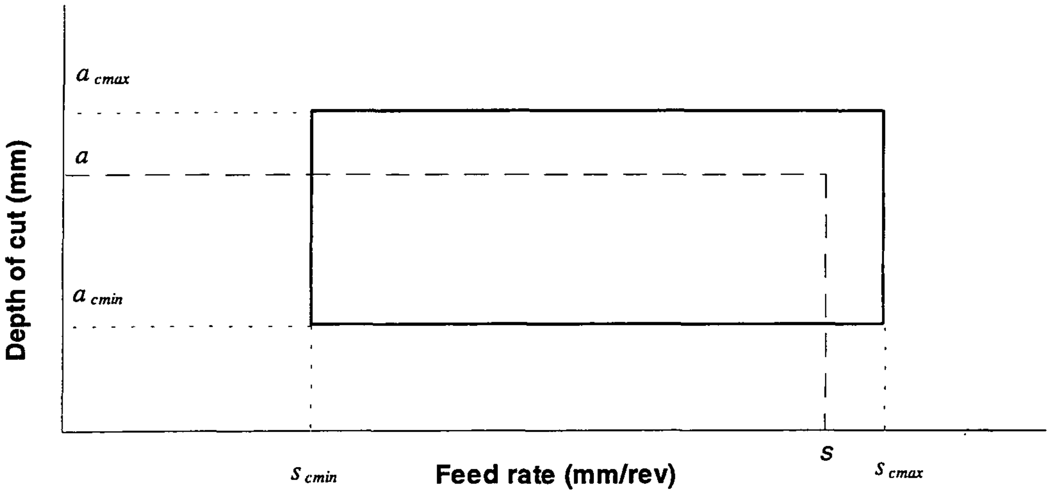

Figure 3.3 Chipbreaker application range diagram.

- *Feed rate*

For finishing operations the surface finish and tolerances are affected by the combination of nose radius and feed rate as well as the workpiece stability, clamping and the overall condition of the machine tool. The surface finish can often improve by using higher cutting velocities and neutral or positive rakes [Sandvik Coromant 1993]. According to the surface roughness requirement (R_a) and the selected insert nose radius (r_e), the maximum allowable feed rate can be calculated as follows [Maropoulos 1990]:

$$s_{r\,max} = (0.0312\ r_e\ R_a)^{0.5} \tag{3.2}$$

Once the maximum allowable feed rate is computed, it will be checked against the chipbreaker application range and the maximum feed rate is given by:

$$s = s_{max} = \min\,(s_{r\,max},\ s_{c\,max})$$

Figure 3.3 shows the initial values of a and s which must be within the chipbreaker's application range.

3.1.5.2 Roughing operation

- *Depth of cut*

The maximum depth of cut achievable by the shape of a tool holder (i.e. approach angle and length of the cutting edge) can be calculated as follows:

$$a_{t\,max} = \frac{2}{3}\ l_e\ \sin K \tag{3.3}$$

where; l_e is the length of cutting edge and K is the tool's approach angle. The depth of cut is set equal to this maximum value; $a = a_{max} = a_{t\,max}$.

This value must be within the capabilities of the given insert and the depth of cut is set equal to the maximum chipbreaking value ($a = a_{max} = a_{c\ max}$), if $a_{t\ max} > a_{c\ max}$, or equal to the minimum chipbreaking value ($a = a_{max} = a_{c\ min}$), if $a_{t\ max} < a_{c\ min}$.

The number of passes (n_{passes}) required to machine the total stock (a_{stock}) when the depth of cut is a_{max} can be calculated as follows:

$$n_{passes} = int\left(\frac{a_{stock}}{a_{max}} + 0.99\right) \tag{3.4}$$

The value of n_{passes} is rounded to the next higher integer number.

Then the final depth of cut is:

$$a = \frac{a_{stock}}{n_{passes}} \tag{3.5}$$

- *Feed rate*

The maximum feed rate for a roughing cut can be calculated using the following empirical formula:

$$s_{r\ max} = 0.8\ r_e \tag{3.6}$$

Initially, the feed rate is set equal to this maximum value, $s = s_{r\ max}$. If $s_{r\ max} > s_{c\ max}$, the new value is set equal to the maximum chipbreaker value ($s = s_{max} = s_{c\ max}$) whilst, $s = s_{max} = s_{c\ min}$, if $s_{r\ max} < s_{c\ min}$.

The calculated depth of cut and feed rate values will be the initial cutting parameters for a roughing operation.

3.1.6 Cutting forces

The cutting forces acting on the tool are an important aspect of machining operations. For those concerned with the manufacturing of machine tools, a knowledge of the cutting forces is needed for the estimation of power requirements and for the design of structures adequately rigid and free from vibration. The cutting forces vary with the tool angles and component material and accurate estimation or measurement of forces is required in optimizing the machining conditions. For a semi-orthogonal cutting operation in lathe turning, the cutting force can be resolved in three directions. The component of the force acting on the rake face of the tool, normal to the edge in the direction of cutting velocity is called the cutting velocity force component (f_v). This is usually the largest of the three force components. The force acting on the tool which is parallel to the direction of the feed rate, is referred to as the feed force (f_s). The third force component, f_a, is in the direction of the depth of cut and is the smallest of the three force components. The velocity force component (f_v) can be calculated by using this formula:

$$f_v = K_{corr} K_{sm} (a\ s) \tag{3.7}$$

where; K_{sm} is the specific resistance to cut of the material and gives the force required for removing a chip of a cross section of 1 mm^2 (Table 3.1). The K_{sm} value is defined as:

$$K_{sm} = \frac{f_v}{A} = \frac{\text{velocity cutting force}}{\text{chip area}} \quad (\text{N/mm}^2) \tag{3.8}$$

The K_{sm} value, however, varies not only with the material properties but also depends on factors such as:

- Insert geometry.
- Entering angle of the tool.
- Feed rate.

The effect of the first two factors is difficult to accurately predict and is smaller than that of the feed rate. Therefore, TPO considers the effect of the feed rate on K_{sm}. The K_{sm} value is corrected by using a correction factor (K_{corr}) for different feed rates. K_{corr} depends upon several factors such as the chip thickness and deformation energy and has low values for high feed rates and high values for low feed rates. Table 3.2 shows the values of K_{corr} for several different feed rates [Sandvik Coromant, 1985].

Table 3.2 K_{corr} Correction factors for feed rates

Feed rate (mm/rev)	*0.1*	*0.15*	*0.2*	*0.25*	*0.3*	*0.35*	*0.4*
K_{corr}	*1.49*	*1.32*	*1.22*	*1.14*	*1.06*	*1.03*	*1.00*
Feed rate (mm/rev)	*0.5*	*0.6*	*0.7*	*0.8*	*1.0*	*1.02*	*1.4*
K_{corr}	*0.94*	*0.89*	*0.85*	*0.82*	*0.77*	*0.72*	*0.69*

The other two force components can be calculated using a given force ratio between the force components which is assumed to be constant and independent of the workpiece material. However, the force ratio depends on the approach angle of the tool and varies with the type of operation (i.e. finishing or roughing). The following ratio is used by TPO [Maropoulos, private correspondence]:

$$f_v : f_s : f_a = 4.2 : 2.5 : 1.0 \tag{3.9}$$

The three calculated components of the cutting force will then be calculated in order to take them into consideration for further force-related checks.

3.1.7 Force constraints

Having calculated the cutting force components acting on the cutting tool, TPO also calculates the three maximum forces due to constraints in the three main directions, using the following formulas [Maropoulos 1990, 1991]:

$$f_{v1} = \frac{\mu\ f_g\ clmdia}{cpdia} \tag{3.10}$$

where; f_{v1} is the maximum velocity force allowed before the workpiece starts rotating inside the chuck, μ is the coefficient of friction ($\mu = 0.3$), f_g is the clamping force (N), *clmdia* is the clamping diameter inside the chuck (mm), and *cpdia* is the machining diameter (mm) as shown in Figure 3.4.

$$f_{v2} = \frac{0.5\ (clmlen\ +\ \mu\ clmdia) f_g}{\sqrt{3}\ cpdist} \tag{3.11}$$

where; f_{v2} is the maximum velocity force before the workpiece is thrown out of the chuck (N), *clmlen* is the length of the workpiece inside the chuck (mm), *cpdist* is the maximum distance of the tool from the face of the chuck (mm).

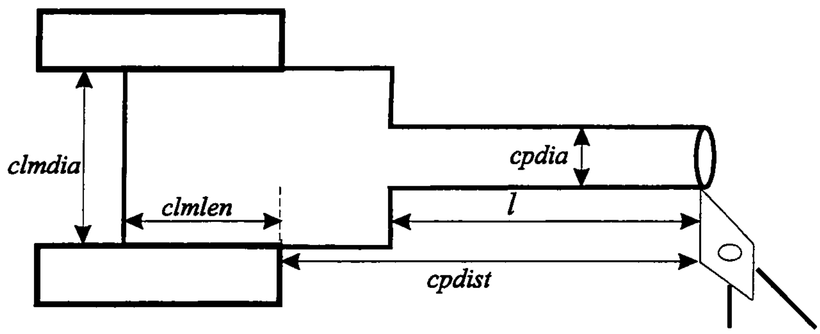

Figure 3.4

Finally, f_{v3}, is the velocity force which utilizes the maximum machine tool power.

$$f_{v3} = \frac{60000\ P_{max}}{v_{max,\ power}} \tag{3.12}$$

The cutting velocity $v_{max,power}$, can be calculated from the formula:

$$v_{max,\ power} = \frac{\pi\ cpdia\ n_{max}}{1000} \tag{3.13}$$

where; P_{max} is the maximum machine power (N), and n_{max} is the maximum spindle speed (rpm) for maximum power as shown in Figure 3.5. For most machine tools, maximum power is obtained over a range of spindle speed and Figure 3.5 shows the capability of the CNC-1000 lathe which was used in the experimental work. Using the maximum spindle speed in equation 3.13 results in high values for $v_{max,power}$ which in turn reduces the f_{v3} value.

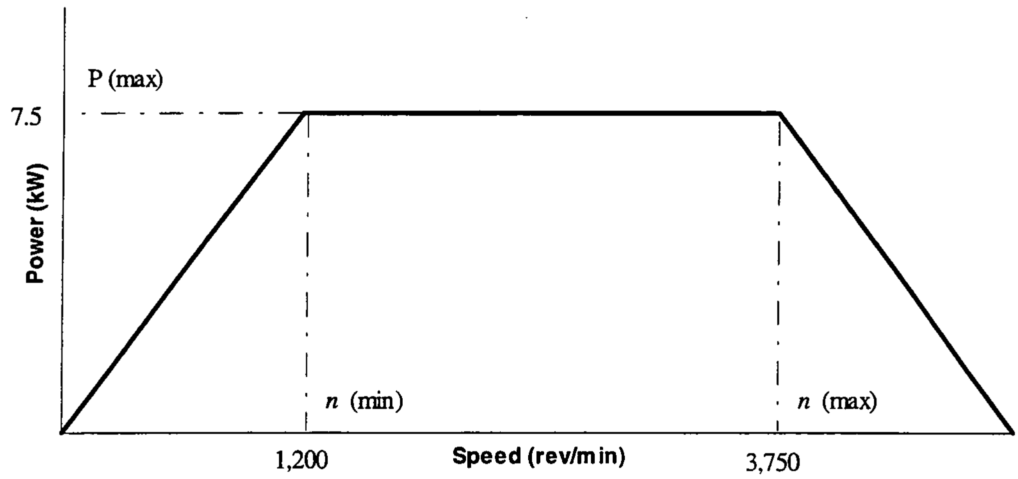

Figure 3.5 Power-speed diagram of the machine tool CNC-1000

For turning operations, the velocity cutting force (f_v) must be less than the minimum constraint force in the velocity direction, f_{v1}, f_{v2}, and f_{v3}.

$$f_v \leq min\ (f_{v1}, f_{v2}, f_{v3}) \tag{3.14}$$

If this check fails, TPO will set:

$$f_{v,new} = min\ (f_{v1}, f_{v2}, f_{v3})$$

Initially, it is attempted to obtain the reduced velocity force component by reducing the feed rate for the same depth of cut.

$$s_{new} = \frac{f_{v,new}}{K_{corr}\ K_{sm}\ a} \tag{3.15}$$

The feed rate can be reduced up to the minimum chipbreaking value ($s_{c\ min}$). When $s_{new} < s_{c\ min}$, the depth of cut should be reduced by increasing the number of passes by one and resetting the feed rate to its initial value.

$$n_{passes,new} = n_{passes} + 1 \tag{3.16}$$

and

$$a_{new} = \frac{a_{stock}}{n_{passes,new}} \tag{3.17}$$

The above process will be repeated until the condition in equation (3.14) is satisfied.

- *Axial and radial force constraints*

The maximum axial force before the workpiece starts sliding in the chuck is calculated as follows:

$$f_{axial} = \mu \, f_g \tag{3.18}$$

where; f_{axial} is the maximum axial force to prevent axial slip of the workpiece in the chuck (N).

The cutting force deflects the workpiece and in the case of single point workholding, the maximum radial force f_{radial} allowed can be calculated as follows:

$$f_{radial} = \frac{3 \; elc \; defcom}{cpdist^3} \quad \text{(N)} \tag{3.19}$$

where; $defcom = \frac{1}{2}(diametral\ tolerance)$

$$elc = \frac{E \; \pi \; (D_{ext}^4 - D_{int}^4)}{64} \tag{3.20}$$

where; E is Young's module of elasticity. The *diametral tolerance* is set by default to 0.03 mm. The user can specify any other value.

For longitudinal operations, the feed force (f_s) and the force acting in the direction of depth of cut (f_a) calculated by equation 3.9, should be less than or equal to the calculated axial force (f_{axial}) and radial force (f_{radial}) respectively.

$$f_s \leq f_{axial}$$

and

$$f_a \leq f_{radial}$$

For facing operations the direction of the cutting force f_s and f_a is reversed and the system will check the force f_a to be less than or equal to the axial force constraint (f_{axial}), and the feed rate force (f_s) to be less than or equal to the radial force constraint f_{radial}.

$$f_s \leq f_{radial}$$

and

$$f_a \leq f_{axial}$$

If the last two checks fail, the system will reduce the value of the feed rate and of the depth of cut as described in the case of the velocity force. At the end of this process all force related constraints have been satisfied and the values of depth of cut (a) and feed rate (s) are accepted as feasible cutting conditions.

3.1.8 Cutting velocity

Based on the type of cut (finishing, medium roughing or roughing operation), TPO shows the user a range of cutting velocities recommended by tool manufacturers to cut the selected material sub-class by the selected grade. The user is required to select a value of cutting velocity (v).

- *Rotational speed check*

The spindle speed corresponding to the selected value of cutting velocity can be calculated from the following formula:

$$n = \frac{1000\ v}{\pi\ D} \quad \text{(rpm)} \qquad (3.21)$$

The rotational speed (n) should be within the speed range of the selected machine ($n_{min} \le n \le n_{max}$) as shown in Figure 3.5. If it is less than the machine minimum the calculated value will be set equal to the minimum ($n = n_{min}$). If it is greater than the maximum machine speed the calculated rpm value will be reduced to the maximum spindle value ($n = n_{max}$). A new sub-optimal cutting velocity (v) will then be calculated using equation (3.21).

- *Power check*

The power required for metal cutting is mainly of interest during roughing, when it is essential to ensure that the machine has sufficient power for the operation. The basic parameters in the power calculation are the rotational cutting force velocity, f_v , and the cutting velocity (v). The efficiency factor of the machine is also important. The efficiency factor (η), depends on the type of transmission the machine is fitted with, and the overall machine condition. The machine efficiency is normally between 0.6 to 0.9, and η = 0.75 is used within the system. The required power can be calculated as follows:

$$Power = \frac{f_v \, v}{60000\eta} \quad \text{(Kw)} \qquad (3.22)$$

The calculated power should be less than or equal to the maximum machine power ($P \leq P_{machine}$). If this test fails, the power will be set equal to the maximum machine power and the final cutting velocity can be recalculated using equation (3.22). After the execution of the algorithm described above the three cutting parameters (a, s and v) of a machining operation have been calculated.

Chapter 4

TOOL LIFE PREDICTION

This chapter describes the tool life prediction (TLP) module. The first task of any computer-based system is to define the problem the user is trying to solve. TLP accomplishes this through a series of interactive decision trees in which the user specifies interactively the characteristics of the required machining operation by selecting a component using the appropriate user interface window. A number of operations (up to 5 operations) are displayed on the screen and the user must select one operation. The essential information required by TLP is in relation to the cutting conditions (cutting velocity and feed rate), tool code, insert grade, type of cut, type of cutting fluid, machine tool and the material class and sub-class. The technical planning of an operation creates most of this information as described in Chapter three. However, at this level there is a need to re-confirm certain elements of the operation which have a direct influence on tool life. The workpiece material and tool's carbide grade belong to this category.

To describe a work material, the user chooses from a list of material classes (mild and alloy steels, stainless steels, cast iron, aluminium etc.) as shown in Table 3.1. Within the general material class there are usually several sub-classes, for example, for stainless steel there are free-cutting stainless steel, moderately difficult to cut stainless steel or difficult to machine stainless steel. The user selects a sub-class and based on the chosen work material a set of feasible carbide grades are selected and displayed on the screen. The user selects the carbide grade and the type of cut (finishing, semi-roughing or roughing), and TLP creates and displays a graph of cutting velocity against tool life, based on the theoretical tool life data. This is in order to guide the user to enter a reasonable cutting velocity for a given feed rate value. Various $(T \; vs \; v)$ graphs can be created for different feed rate values. Using this information, the user can confirm the cutting velocity retrieved from the operations database or enter another value.

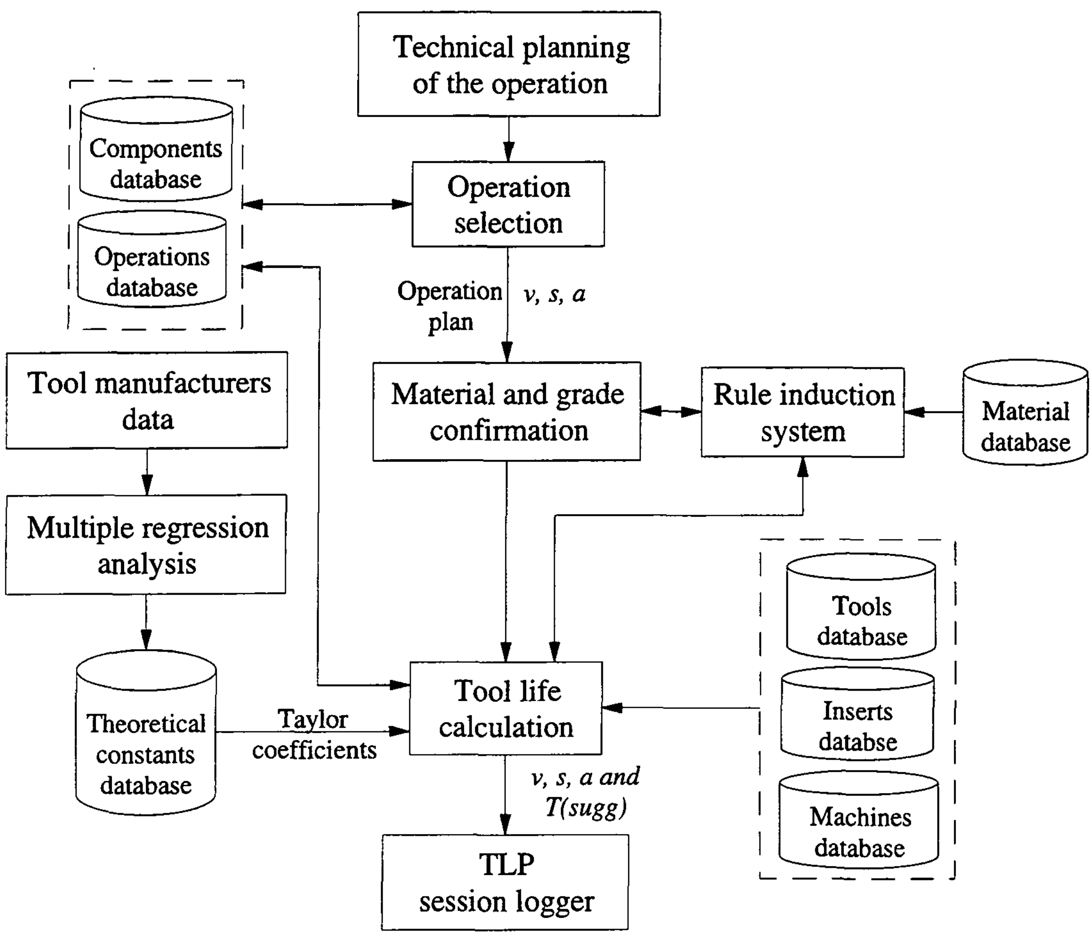

Figure 4.1. Overall Structure of Tool Life Prediction Module

The tool life value predicted by TLP is used as an initial recommendation based on theoretical data and is later considered by the tool life assessment module of the system. Figure 4.1 shows the structure of TLP and a more detailed description of its functionality follows.

4.1 AUTOMATIC RULE INDUCTION SYSTEM

The automatic rule induction system is a front-end system to *Crystal.* It will automatically turn a table of material values such as the chemical percentage compositions for a number of materials within each material sub-class, into a well structured set of *Crystal* rules which describe the relationship between the given values. The *Crystal induction system* creates rules which are used for defining the material sub-class of a new material from its percentage chemical composition. The rules for each sub-class are robust because in the tool life control system there are seven main material classes based on tool manufacturers data (Table 3.1) and each material class is further sub-divided into several sub-classes (32 in total). The *Crystal induction system* looks for attributes that split each of these material sub-class and creates rules automatically from these examples which define the composition limits of each material sub-class. The rules created by the induction system are well structured and easily extendible within the *Crystal* program.

The chemical percentage composition and the Brinell hardness for all the material sub-classes within each material class were collected [Metcut Res. Assoc. 1980; Wegst 1992; Soc. Auto. Engs. 1981] and fed into the rule induction system to generate rules and conditions which define the limits of each sub-class. Table 4.1 shows the chemical composition of the iron base alloy sub-class material of the heat-resistant super alloy class.

Table 4.1 shows fourteen materials belonging to this sub-class. The complexity of the information is apparent since there are eleven alloying elements. This table is processed by the rule induction system and a complex rule concerning the chemical composition of all members of this sub-class is constructed.

Table 4.1 Chemical percentage composition of some iron alloy base sub-class materials

USA	*UK*	*Fe*	*Ni*	*Co*	*Cr*	*Mo*	*W*	*Si*	*Mn*	*C*	*AI*	*TI*
ASTM: 638	HR 5152	53.65	26.0	-	15.0	1.3	-	0.5	1.3	0.05	0.2	2.0
ATM: A638		54.26	26.0	-	13.5	2.7	-	0.8	0.9	0.04	0.1	1.7
5725		50.53	25.0	-	16.0	6.0	-	0.7	1.35	0.12	-	0.3
AISI: 615		80.98	2.0	-	13.0	0.15	3.0	0.3	0.4	0.17	-	-
5768		33.40	20.0	20.0	21.0	3.0	2.5	-	-	0.1	-	-
ASME : SB 163	3082-76	44.85	32.5	-	21.0	-	-	0.5	0.8	0.05	0.4	0.4
5552		45.05	32.0	-	20.5	-	-	0.5	0.8	0.05	-	1.1
	3072-76	41.64	37.0	-	18.0	-	-	2.3	1.0	0.06	-	-
5718/9		83.65	2.5	-	12.0	1.7	-	-	-	0.15	-	-
5768		31.35	20.0	20.0	21.0	3.0	2.5	0.5	1.5	0.15	-	-
5533		30.57	20.0	20.0	21.0	4.0	4.0	-	-	0.43	-	-
AISI: 663		52.57	27.0	-	14.8	1.25	-	0.75	0.3	0.08	0.25	3.0
AISI: 665		53.97	26.0	-	13.5	1.5	-	0.4	1.5	0.08	0.2	2.85
ASTM: A477		68.0	9.0	-	19.0	1.0	1.0	0.6	1.1	0.3	-	-

The rule created by the induction system for defining the iron base alloy sub-class material within the heat resistance super alloy class is as follows:

IF Cu is less than 42.950

AND Ni is less than 34.000

AND Co is less than 29.000

AND Ti is less than 37.825

AND NOT Fe is less than 15.225

OR Cu is less than 42.950

AND NOT Ni less than 34.000

AND NOT C is less than 0.020

AND Ni is less than 49.050

AND NOT Fe is less than 38.470

The user can induce the use of the rule induction system by selecting the "Unknown" option when asked to select from the material sub-class list in the *Crystal* program. The user is prompted to supply information concerning the material chemical composition and/or its Brinell hardness range. Then the rule induction system can define the sub-class of the user defined material as described above. Having defined the sub-class, TLP retrieves the theoretical constants for the calculation of tool life.

4.2 CALCULATIONS OF THE THEORETICAL TOOL LIFE CONSTANTS

F. W. Taylor (1907) was the first to investigate the relationship between tool life and cutting conditions such as cutting velocity, feed rate and depth of cut. A database of tool supplier's cutting conditions and tool life data [Sandvik Coromant 1993; Seco Tools 1993] for a wide range of carbide tools and different workpiece materials, was analyzed using multiple regression to calculate the theoretical coefficients of the extended form of *Taylor's* equation (lnC, $\frac{1}{\alpha}$, $\frac{1}{\beta}$).

$$T = \frac{C}{v^{1/\alpha} s^{1/\beta}} \tag{4.1}$$

Equation 4.1 does not directly include the influence of depth of cut. This is incorporated in the constant *C*. The tool life coefficients are calculated for the three types of operations namely, finishing, medium-roughing and roughing. *Appendix 2* shows the form of the input data tables, relating a carbide grade to a material sub-class for finishing, medium roughing and roughing operations. The cutting data shown in *Appendix 2* will result in tool life of approximately 15 minutes, but this is dependent on other factors such as chipbreaker type, set-up stability of the part, machine tool condition, stability of the tool and tool overhang. Tool manufacturers advise that to achieve longer tool life, one should multiply the recommended cutting velocities by the following simplistic empirical factors:

Target Tool Life (min)	Velocity Factor
30	0.86
45	0.79
60	0.74

These simple, empirical factors were used to create additional sets of cutting data and tool life and calculate initial values for the tool life constants. The initial clustering of tool life predictions induced by applying these simple factors is eliminated by applying a continual feedback process by collecting and processing real tool life values from the shop floor.

Multiple regression techniques allow the calculation of the tool life coefficients as shown in *Appendix 3*. The coefficients are stored in the tool life constants database and are subsequently used to predict tool life. Table 4.2 shows the calculated tool life constants for machining free cutting steel (EN8) using TP10 and TP20 insert grades under finishing, semi-roughing and roughing cutting conditions as well as for machining difficult stainless steel (SS 316) using TP35 insert grade. The details of using the multiple regression method to calculate the coefficients of the linear form of *Taylor's* tool life equation are described in the next section.

Table 4.2 Tool life constants calculated by multiple regression

Material sub-class	***Insert grade***	***Type of cut***	***ln C***	***1/α***	***1/β***
	TP10	Finishing	29.690	4.584	0.298
	"	Semi-roughing	23.015	3.446	0.000
	"	Roughing	22.847	3.478	0.000
Free cutting steel	TP20	Finishing	29.072	4.612	0.292
	"	Semi-roughing	25.600	4.531	2.596
	"	Roughing	23.987	4.309	2.503
Difficult stainless steel	TP35	Finishing	14.609	2.548	0.060
	"	Semi-roughing	21.501	4.307	0.000

4.2.1 Multiple Regression

Multiple regression takes into account the effect of more than one independent variable, such as cutting velocity (v) and feed rate (s), on the dependent variable which is tool life (T) [Wonnacott 1990]. The relationship between the dependent variable T and the two independent variables v and s in the linear form is:

$$\ln T = \ln C + (-1/\alpha)\ \ln v + (-1/\beta)\ \ln s \tag{4.2}$$

Different v_i and s_i result in different T_i and equation 4.2 will have the form:

$$\ln \hat{T_i} = \ln C + (-1/\alpha)\ \ln v_i + (-1/\beta)\ \ln s_i \tag{4.3}$$

$\ln \hat{T_i}$ is the expected value of $\ln T_i$. The difference between the observed and expected values of $\ln T_i$ is the stochastic error term (e_i). Thus, any observed value $\ln T_i$ may be expressed as its expected value plus this disturbance term.

$$\ln T_i = \ln C + (-1/\alpha)\ \ln v_i + (-1/\beta)\ \ln s_i + e_i \tag{4.4}$$

The Least Squares method is driven by selecting the estimates of $\ln C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$ that minimize the sum of the squared deviations between the observed and the estimated values of $\ln T$; that is, minimize:

$$\sum \left[\ln T_i - \ln \hat{C} - (-\hat{\frac{1}{\alpha}})\ \ln v_i - (-\hat{\frac{1}{\beta}})\ \ln s_i \right]^2 \tag{4.5}$$

where; $\ln \hat{C}$, $\hat{\frac{1}{\alpha}}$, $\hat{\frac{1}{\beta}}$ are the estimated values of $\ln C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$. This is done by setting the partial derivatives of the above function with respect to $\ln \hat{C}$, $\hat{\frac{1}{\alpha}}$, $\hat{\frac{1}{\beta}}$ equal to zero.

This gives the following three equations:

$$\sum\left[\left(\ln v_i - \overline{\ln v}\right)\left(\ln T_i - \overline{\ln T}\right)\right] =$$

$$(-\hat{\frac{1}{\alpha}})\sum\left[\ln v_i - \overline{\ln v}\right]^2 + (-\hat{\frac{1}{\beta}})\sum\left[\left(\ln v_i - \overline{\ln v}\right)\left(\ln s_i - \overline{\ln s}\right)\right] \tag{4.6}$$

$$\sum\left[\left(\ln s_i - \overline{\ln s}\right)\left(\ln T_i - \overline{\ln T}\right)\right] =$$

$$(-\hat{\frac{1}{\alpha}})\sum\left[\left(\ln v_i - \overline{\ln v}\right)\left(\ln s_i - \overline{\ln s}\right)\right] + (-\hat{\frac{1}{\beta}})\sum\left[\ln s_i - \overline{\ln s}\right]^2 \tag{4.7}$$

$$\ln \hat{C} = \overline{\ln T} - (-\hat{\frac{1}{\alpha}})\,\overline{\ln v} - (-\hat{\frac{1}{\beta}})\,\overline{\ln s} \tag{4.8}$$

Appendix 4 shows these calculations for TP20 insert grade when cutting free-cutting steel material under medium roughing machining conditions.

4.3 TOOL LIFE CALCULATION CRITERIA

The prediction module has access to seven databases namely, tools, inserts, machines, material, theoretical tool life constants and the approved database as shown in Figure 4.1. The first three databases are essential for reading information such as cost, chipbreaking range, machine power and speed range in order to calculate the overall machining constraints. The material properties database is used by the rule induction system to define the material sub-class of a user defined material. For the same insert grade, workpiece material and type of cut, TLP retrieves the tool life coefficients from the fifth database (constants database) and calculates the theoretical tool life value. The prediction module calculates the tool life value according to the following criteria:

- Tool life for user defined cutting conditions.

- Tool life for minimum production cost.
- Tool life for minimum production time.

4.3.1 Tool life for user defined cutting conditions

For any given cutting conditions (v and s), the tool life is calculated using the linear form of Taylor equation.

$$ln T_i = ln \hat{C} + (-1/\hat{\alpha})\, ln\, v_i + (-1/\hat{\beta})\, ln\, s_i \quad (4.9)$$

The relationship between cutting data and tool life can be used for optimising the economics of the cutting process. Two distinct criteria can be used for choosing the cutting velocity for a machining operation; minimum production cost and minimum production time.

4.3.2 Tool life for minimum production cost

The time spent by the operator in producing w batches of size q can be separated into three items:

$w\, q\, t_1$ = Work set up time, where t_1 is the time taken to load and unload each component.

$w\, q\, t_2$ = Machining time, where t_2 is the machining time.

$N_e\, t_3$ = Tool changing time, where t_3 is the time to change an individual tool and N_e is the number of cutting edges used. At this stage it is assumed that N_e is equal to the number of machine stops for tool changing.

Thus, if x is the total machine and operator rate (including overheads), the total machine and operator costs will be:

$$x\,(\,w\,q\,t_1 + w\,q\,t_2 + N_e\,t_3\,) \tag{4.10}$$

This cost must be added the cost of the tool used, $N_e\,y$, where y is the cost per cutting edge. The average production cost, C_{pr}, for each component is:

$$C_{pr} = x\,t_1 + x\,t_2 + [\,N_e/(\,w\,q\,)]\,x\,t_3 + [\,N_e/(\,w\,q\,)]\,y \tag{4.11}$$

The first term in this equation is the non-productive cost due to work set up which is constant for the particular operation. The second term is the machining cost, which reduces as the cutting velocity increases at constant feed rate. The final two items are giving the tool costs, which increase as the cutting velocity increases. Figure 4.2, shows the empirical relationship between the cutting velocity and the tool life [Taylor 1907]:

$$\frac{v}{v_r} = \left(\frac{T_r}{T}\right)^{\alpha} \tag{4.12}$$

where; v is the cutting velocity; T is the tool life; α is constant, and T_r is the measured tool life for a given cutting velocity v_r.

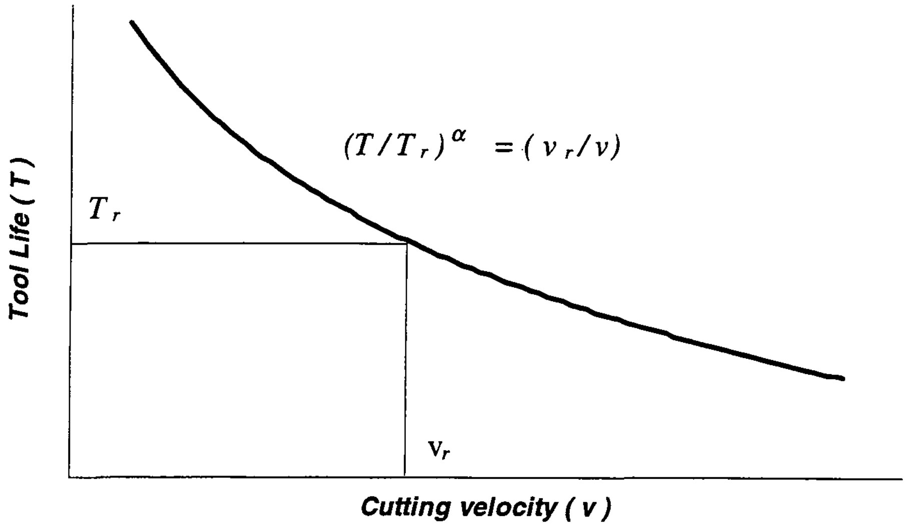

Figure 4.2 The relationship between tool life and cutting velocity.

The tool life T is given by:

$$T = T_r \left(\frac{v_r}{v} \right)^{1/\alpha} \tag{4.13}$$

The number of edges N_e used in machining w batches of size q is given by $(w\ q\ t_2 / T)$, assuming that the tool is engaged with the workpiece during the entire machining time. Thus,

$$\frac{N_e}{w\,q} = \frac{t_2}{T} = \frac{t_2}{T_r} \left(\frac{v}{v_r} \right)^{1/\alpha} \tag{4.14}$$

Finally, the machining time for one component is given by:

$$t_2 = \frac{K}{v} \tag{4.15}$$

where; K is a constant for a particular operation. In cylindrical turning, for example, the value of K will be given by:

$$K = \frac{\pi D l}{s} \tag{4.16}$$

In general, K can be regarded as the distance moved by the cutting edge relative to the workpiece during the machining operation.

The relationship between the production cost and the cutting velocity can be obtained by substituting equations (4.14) and (4.15) in equation (4.11).

$$C_{pr} = x t_1 + x K v^{-1} + \frac{K}{v_r^{1/\alpha} T_r} (x t_3 + y) v^{(1-\alpha)/\alpha} \tag{4.17}$$

To find the cutting velocity (v_{mc}) for minimum cost, equation (4.17) must be differentiated with respect to v and equated to zero. Thus;

$$v_{mc} = v_r \left(\frac{\alpha}{1-\alpha} \frac{x T_r}{x t_3 + y} \right)^{\alpha} \tag{4.18}$$

By substituting equation (4.18) into equation (4.13), the optimum tool life for minimum cost (T_{mc}) is :

$$T_{mc} = \frac{1-\alpha}{\alpha} \left(\frac{x t_3 + y}{x} \right) \tag{4.19}$$

The cost per cutting edge (y) for an indexable insert can be calculated as follows [Maropoulos and Hinduja 1990]:

$$y = \frac{Insert\ cost}{0.75 \times number\ of\ cutting\ edges} + \frac{1.3 \times Holder\ cost}{400} \tag{4.20}$$

4.3.3 Tool life for minimum production time

To find the optimum cutting velocity for maximum production rate (or minimum production time) v_{mt}, it is necessary to follow a similar procedure to that described in section 4.3.2. The average production time for one component is given by:

$$t_{pr} = t_1 + t_2 + \frac{N_e}{w\,q}\,t_3 \tag{4.21}$$

Substitution of equations (4.14) and (4.15) in equation (4.21) and differentiation gives the cutting velocity (v_{mt}) for minimum production time.

$$v_{mt} = v_r\left(\frac{\alpha}{1-\alpha}\,\frac{T_r}{t_3}\right)^{\alpha} \tag{4.22}$$

The optimum tool life for minimum production time (T_{mt}) can be obtained by substituting equation (4.22) in equation (4.13).

$$T_{mt} = \left(\frac{1-\alpha}{\alpha}\right)t_3 \tag{4.23}$$

Finally, the cutting velocity (v) and the spindle speed (n) are calculated using Taylor's tool life equation (4.1).

$$v = \left(\frac{C}{T\,s^{1/\beta}}\right)^{\alpha} \tag{4.24}$$

$$n = \frac{1000\;v}{\pi\;D} \tag{4.25}$$

where, D is the effective (generated) machining diameter (mm).

The calculated spindle speed should be within the rotational speed range of the selected machine as described in Section 3.1.8. If the rotational speed (n) must be modified, new cutting velocity is obtained using equation 4.25.

The results from TLP are displayed on the results screen, together with a question asking whether they are acceptable. If the user replies "NO", TLP restarts the process for calculating the tool life with different options given by the user. If the user answers "YES", the results will be saved automatically in the TLP session logger. Then the user can decide whether the results should also be saved in the system's database. A number of results can be stored temporarily in the session logger when the user wishes to continue with the assessment of those predictions using approved information as will be described in Chapter 6. The TLP session logger is a dynamic file created by the module in order to save the TLP calculation for the operation under consideration. Up to ten operations can be saved in the session logger file.

The session logger can be accessed from the next module of the system, the tool life assessor TLA. Any operation can be selected from the session logger to be considered as an input for TLA.

Chapter 5

INITIAL TOOL LIFE TESTS

A series of experiments were designed and completed to test the accuracy of the theoretical tool life predictions. The cutting tests were carried out by turning free cutting steel (EN8) and difficult to machine stainless steel (316) using three different coated carbide grades (TP10, TP20, and TP35). The calculation of cutting conditions was based on the algorithmic method implemented in the technical planning module (TPO). The suggested tool life values (T_{sugg}) predicted by TLP were based on the theoretical tool life constants generated by multiple regression as shown in Table 4.2 in Chapter 4. The main objectives for the initial experimental work were:

- To establish the effect of cutting conditions on tool life for different insert grades, workpiece materials and types of cut.
- To study the relationship between the flank wear rate and machining time.
- To validate the operation of the first two modules namely, TPO and TLP, in relation to their main functions.
- To build the approved tool life history which will be used by the tool life assessor module (TLA).

5.1 APPARATUS USED

5.1.1 The centre lathe

The Colchester CNC-1000 centre lathe shown in Figure 5.1 was used for the tests. The CNC-1000 was specifically designed for jobbing shops and tool rooms and has a maximum power of 7.5 kW (30 minute rated), whilst its maximum power for constant operation is 5 kW. The maximum spindle speed is 3750 rev/min as shown in Figure 3.5. This lathe has a robust headstock design with a heavy-duty precision spindle that offers high radial load capacity and guarantees roundness accuracy better than 2 μm.

Figure 5.1 Colchester CNC-1000 centre lathe

5.1.2 Tool holder and inserts

The tool holder geometry for the tests was the widely employed PCLNR2020-12A and the carbide inserts had nose radii of 0.4 and 0.8 mm as shown in Figure 5.2. Three types of carbide grades were tried (TP10, TP20 and TP35), corresponding to the *ISO* P10, P20 and P35 application ranges. The chipbreaking geometries employed were suitable for light to medium roughing machining operations. The chipbreaking geometry employed with TP10 and TP20 insert grades when finish machining free cutting steel (EN8) was MF2. MF2 limits the depth of cut in the range between 0.5 and 3.5 mm and the feed rate between 0.1 and 0.4 mm/rev. The MF3 chipbreaker was used on TP20 and TP35 insert grades to cut free cutting and difficult stainless steel (316) respectively. The application range of MF3 limits the depth of cut between 1 and 4 mm and the feed rate between 0.1 and 0.4 mm/rev.

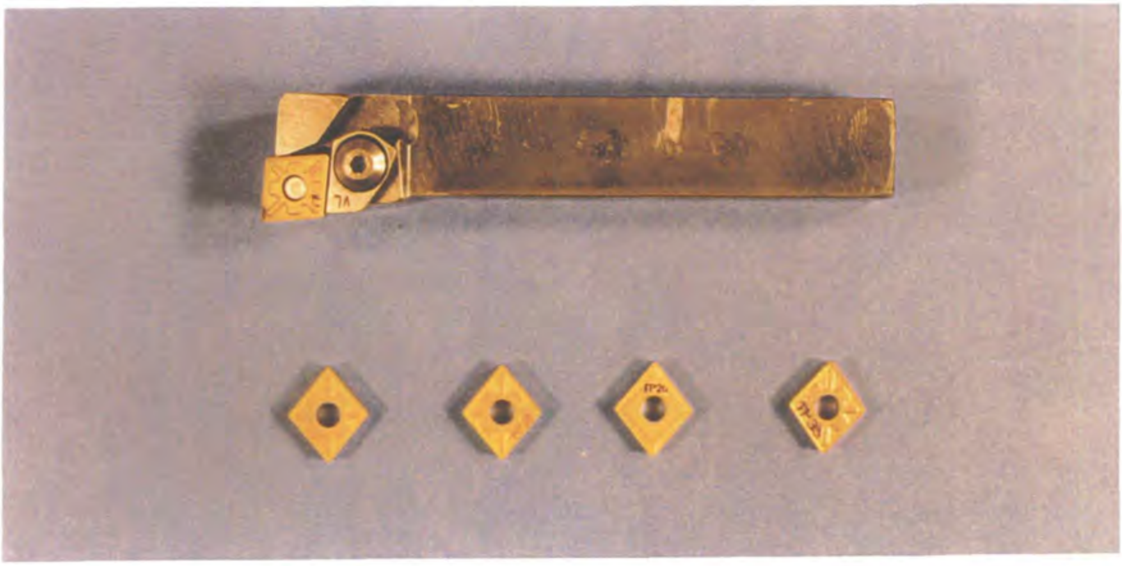

Figure 5.2 PCLNR-2020_12A and the carbide inserts used in the initial tests.

5.1.3 Workpiece material

Two types of workpiece materials were used for the tests. The first workpiece material was BS080A40 (EN8) free cutting steel and its specific resistance to cut is approximately 2100 N/mm^2 depending on the feed rate used. The second type of workpiece material was (SS316), which is difficult to machine austenitic stainless steel and its specific resistance to cut is approximately 2500 N/mm^2. Free cutting steels are produced with additions of 0.1% to 0.3% sulphur or 0.3% to 0.35% lead or combinations of both to reduce cutting forces, cutting temperature and hence tool wear rates. These additions allow, for the same wear rate, higher cutting velocities to be applied with improved surface finish. Austenitic stainless steels have high work-hardening rates and low thermal conductivity. Their high work-hardening rate causes high energy consumption. The low thermal conductivity causes high temperature gradients within the chip. The high temperatures in the chip-tool interface result in increased diffusion wear rates.

5.1.4 Measuring microscope

The Carlzeiss Jena 10907 toolmaker's microscope shown in Figure 5.3 was used in these tests. It is equipped with micrometer screws which perform the double function of moving the table laterally and horizontally and provide measurements to the accuracy of 0.0001 in (0.00254 mm). The most common method of measuring is by the use of graticule hair lines. The edge of the part to be measured is lined up with the hair line. At that point, a zero setting can be made on the micrometer dial. The part is then moved until its other edge is lined up with the hair line and the distance noted on the dial.

Figure 5.3 Carlzeiss Jena 10907 microscope used for measuring the flank wear

5.2 TOOL FAILURE CRITERIA

The wear of the face and flank of the cutting tool is not uniform along the active cutting edge. Therefore, it is necessary to specify the locations and the degree of wear when deciding on the amount of wear allowable before replacing the cutting insert. The criteria recommended by the *International Standards Organisation (ISO)* dealing with tool life testing follow [*ISO 3685–1977*]:

- ***High speed steel or ceramic tools***

The failure criteria which give the effective tool life for high speed steel or ceramic tools are:

- Catastrophic failure.
- VB = 0.3 mm if the flank is regularly worn.
- VB_{max} = 0.6 mm if the flank is irregularly worn, scratched, chipped, or badly grooved.

- ***Sintered carbide tools***

One of the following failure criteria is recommended:

- VB = 0.3 mm.
- VB_{max} = 0.6 mm if the flank is irregularly worn.
- KT = 0.06 + 0.3 s , where s is the feed rate.

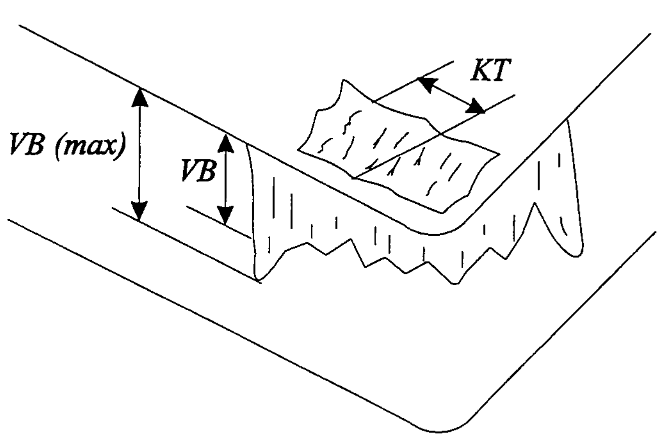

Figure 5.4 The way of measuring tool wear

For this testing phase, a wear land of approximately 0.35 mm was taken as the failure criterion. The reason for setting this criterion was that the measurement of wear was not continuous but instead wear was measured at discrete intervals. In each case a tool was considered to have failed when the measured wear (*VB*) exceeded 0.3 mm, and in most tests the maximum wear land measured was in the range 0.3 – 0.35 mm.

For each test, machining was interrupted after 1–3 minutes in order to measure the size of the flank width VB; i.e. the distance between the straight part of the original major cutting edge and the boundary of the flank wear land as shown in Figure 5.4. This machining time interval (1–3 min) is chosen in order to monitor any change in the rate of creation of the flank wear by taking the exact reading of the flank wear at regular intervals.

5.3 THEORETICAL CALCULATIONS AND RESULTS

The carbide tool life data include four separate sets of cutting conditions. The cutting conditions were calculated using the technical planning of the operation module (TPO) and they were within the range of cutting conditions suggested by tool manufactures as shown in *Appendix 2.* The initial cutting conditions calculated by TPO and the theoretical tool life values predicted by TLP were tested on the CNC-1000 machine tool and the final, approved results were derived. All cutting tests were lubricated by using a continuous flow of a general-purpose cutting fluid *(Rocol-Ultracut 370).* The approved results were then stored in the system's operations database and formed the essential information on which the performance of the tool life assessor (TLA) was evaluated as will be discussed in the next Chapter.

5.3.1 Results from machining free cutting steel (EN8) using TP10 insert grade

The first set of 4 tests were obtained by cutting free-cutting steel (EN8) using a TP10 insert grade under finish-machining conditions. The calculated cutting conditions and the suggested tool life values predicted by TLP using the theoretical tool life constants (Table 4.2, Chapter 4) for these tests are shown in Table 5.1.

The required surface roughness (R_a) varied between 0.5 μm to 1.7μm, to check the TPO module's functionality for calculating cutting conditions which result in different surface roughness values.

Table 5.1 Finish machining of EN8 free-cutting steel with TP10 grade.

Machine Tool		CNC-1000			
Tool Holder		PCLNR2020_12A			
Insert Type		CNMG120408_MF2			
Insert Grade		TP10 (P10)			
Workpiece Dimension		Length=200 mm and Diameter=100 mm			
Cutting Fluid		Rocol-Ultracut 370			
Cutting Parameters	*Test No.*	*Test 1*	*Test 2*	*Test 3*	*Test 4*
	Depth (mm)	1.3	1.5	1.0	1.5
	Feed (mm/rev)	0.15	0.1	0.2	0.18
	Velocity (m/min)	415	450	400	460
Tool Life	T_{sugg} (min)	13.76	10.71	14.95	8.13
Surface Roug.	R_a (μm)	0.95	0.5	1.7	1.3

Figure 5.5 shows the progress of flank wear with machining time for four TP10 indexable inserts when finish machining EN8. The first three tests revealed similar wear rate characteristics. The wear rate in the fourth test had a constant rate for the first 5 – 6 minutes and then increased rapidly with cutting time as shown in Figure 5.5. This higher wear rate can be attributed to the combination of high velocity and high feed rate used in this test. Pictures of some inserts used in these tests are shown in *Appendix 5A*.

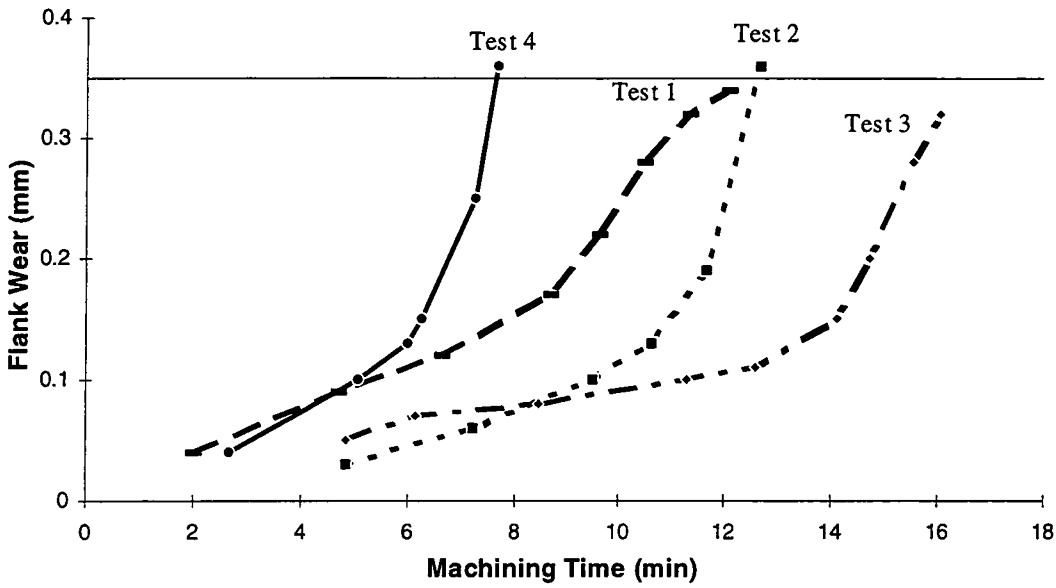

Figure 5.5 Progress of flank wear with time when finish turning EN8 with TP10.

The predicted tool life values using the theoretical tool life constants shown in Table 4.2 are in good agreement with the real, approved values observed in the experiment as shown in Table 5.2. In two tests the theoretical tool life values were higher than those achieved whilst in the other two tests the tool lasted longer than predicted.

Table 5.2 T_{sugg} and T_{app} when finish machining EN8 using TP10

Test number	*Test 1*	*Test 2*	*Test 3*	*Test 4*
T_{sugg} *(min)*	13.76	10.71	14.95	8.13
T_{app} *(min)*	12.08	12.67	16.05	7.7
$\frac{T_{sugg}}{T_{appr}} \times 100\ \%$	114 %	85 %	93 %	106 %

5.3.2 Results from machining free cutting steel (EN8) using TP20 insert grade

The cutting conditions used in these 4 tests to cut EN8 free cutting steel material using TP20 insert grade under finish machining conditions are shown in Table 5.3 together with the tool life values predicted by TLP using the theoretical constants. The surface roughness for these finishing tests varied between 1μm to 1.7μm. It must be noted that in these four tests the feed rates were higher and the velocities lower than the values used in the first series of tests. The reason is that TP20 is tougher but less hard than TP10 hence is withstands higher forces (increased feed) and lower cutting temperature (reduced velocity).

Table 5.3 Finish machining of EN8 free-cutting steel with TP20 grade.

Machine Tool		CNC-1000			
Tool Holder		PCLNR2020_12A			
Insert Type		CNMG120408_MF2			
Insert Grade		TP20 (P20)			
Workpiece Dimension		Length=200 mm and Diameter=100 mm			
Cutting Fluid		Rocol-Ultracut 370			
Cutting Parameters	*Test No.*	*Test 1*	*Test 2*	*Test 3*	*Test 4*
	Depth (mm)	1.5	1.1	1.5	0.7
	Feed (mm/rev)	0.25	0.19	0.2	0.23
	Velocity (m/min)	375	390	395	450
Tool Life	T_{sugg} (min)	8.51	7.7	7.15	3.76
Surface Roug.	R_a (μm)	1.7	1.0	1.1	1.4

The progression of flank wear with machining time when finish machining EN8 free-cutting steel with TP20 insert grade is shown in Figure 5.6. As a result of these four tests, the tool life criterion of $VB_{max} \cong 0.35$ mm was reached after only 3.8 min with cutting velocity of 450 m/min and feed rate of 0.23 mm/rev (see test 4). This means that it is not practical to use a TP20 carbide grade at this velocity and feed range when machining free cutting steel material. The second test shows an early start of the accelerated wear region. This may be due to a degree of "rubbing" during the process because of the relatively small value of the depth of cut (1.1 mm) which is only marginally larger than the tool's nose radius (0.8 mm). Pictures of some inserts employed in this set of tests are shown in *Appendix 5B*.

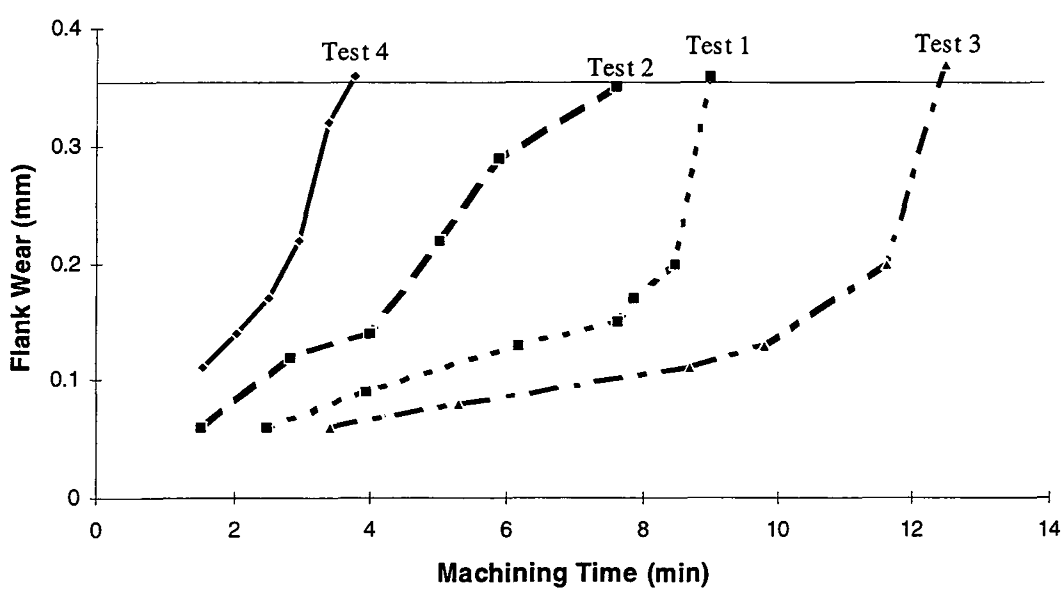

Figure 5.6 Progress of flank wear with time when finish turning EN8 with TP20.

The tool life values suggested by TLP are again very close to the approved values obtained from the experiment except in the third test as shown in Table 5.4. This might be attributed to the fact that the tool manufacturer's recommendations are conservative and also in the particular test the stability of the operation was very good with a positive effect on tool life.

Table 5.4 T_{sugg} and T_{app} when finish machining EN8 using TP20

Test number	Test 1	Test 2	Test 3	Test 4
T_{sugg} (min)	8.51	7.7	7.15	3.76
T_{app} (min)	9	7.58	12.5	3.8
$\frac{T_{sugg}}{T_{appr}} \times 100$ %	95 %	102 %	57 %	99 %

The suggested tool life values and the corresponding cutting conditions employed in 4 semi-roughing tests, in which free cutting steel material was machined using a TP20 insert grade are shown in Table 5.5. The calculated machine power values for all tests are in the range of 5 kW and the spindle speed is approximately in the middle of the machine tool's capability in order to avoid vibrations and workpiece deflection which might affect the overall testing results. It can be seen that the suggested tool lifes are higher than those shown in Table 5.4 and this is mainly due to the use of lower cutting velocities.

Table 5.5 Medium-roughing machining of EN8 free-cutting steel with TP20 grade.

Machine Tool		CNC-1000			
Tool Holder		PCLNR2020_12A			
Insert Type		CNMG120408_MF3			
Insert Grade		TP10 (P10)			
Workpiece Dimension		Length=200 mm and Diameter=100 mm			
Cutting Fluid		Rocol-Ultracut 370			
	Test No.	***Test 1***	***Test 2***	***Test 3***	***Test 4***
Cutting Parameters	Depth (mm)	2.0	2.0	1.7	1.6
	Feed (mm/rev)	0.2	0.2	0.25	0.28
	Velocity (m/min)	350	330	310	295
Tool Life	T_{sugg} (min)	25.43	33.2	24.69	23.03
Mach. Power	P (kW)	5.693	5.368	5.0	4.846
Spindle Speed	*rpm* (rev/min)	1857.75	1751.59	1495.85	1381.6

Figure 5.7 shows the progress of flank wear with machining time for these tests. It is shown that the rate of flank wear for the third and fourth tests increased rapidly with machining time. This can be attributed to the combination of high feed rates and high cutting velocities. Again, pictures of some inserts are shown in *Appendix 5C.*

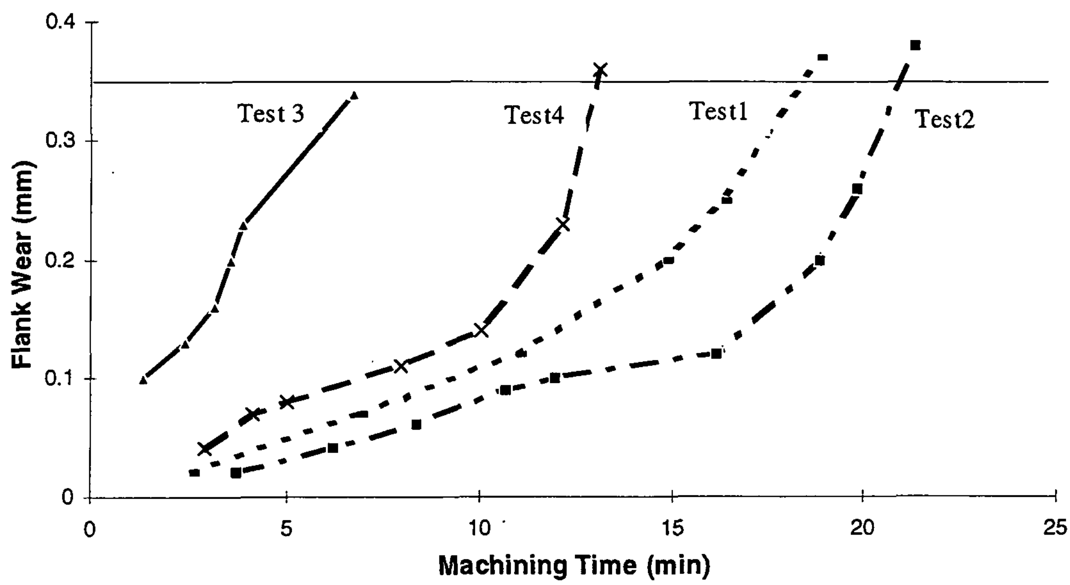

Figure 5.7 Flank wear with time for semi-roughing turning EN8 with TP20.

Table 5.6 shows the suggested tool life values from TLP and the real tool life values obtained from those tests. It is quite clear that the TLP predictions based on theoretical tool life constants result in over estimated tool life values. If these predictions were adhered to by a shop floor operator, catastrophic tool failure would have occurred resulting in scrapped products or damage to the machine tool. These over estimated values might be attributed to the fact that the tool manufacturer's recommendations were based on lower cutting velocities which are normally used for semi-roughing operations. Under these conditions the effect of (v) on tool life is less rapid, and this is reflected in the theoretical value of ($1/\alpha$). However, high values of (v) were used in the tests which resulted in accelerated wear not predicted by the theoretical calculations.

Table 5.6 T_{sugg} and T_{app} when semi-roughing EN8 using TP20

Test number	*Test 1*	*Test 2*	*Test 3*	*Test 4*
T_{sugg} *(min)*	25.43	33.2	24.69	23.03
T_{app} *(min)*	18.8	21.32	6.7	13.13
$\frac{T_{sugg}}{T_{appr}} \times 100\ \%$	135 %	156 %	369 %	175 %

5.3.3 Results from machining difficult stainless steel (316) using TP35 insert grade

The last set of 4 tests were obtained by cutting difficult stainless steel (SS316) using the TP35 insert grade under semi-roughing machining conditions. The calculated cutting conditions and the suggested tool life values predicted by TLP using the theoretical tool life constants for these tests are shown in Table 5.7.

Table 5.7 Semi-roughing machining of 316 stainless steel with TP35 grade.

Machine Tool		CNC-1000			
Tool Holder		PCLNR2020_12A			
Insert Type		CNMG120404_MF3			
Insert Grade		TP35 (P35)			
Workpiece Dimension		Length=200 mm and Diameter=75 mm			
Cutting Fluid		Rocol-Ultracut 370			
Cutting Parameters	*Test No.*	*Test 1*	*Test 2*	*Test 3*	*Test 4*
	Depth (mm)	3.0	3.0	3.0	3.0
	Feed (mm/rev)	0.25	0.3	0.4	0.4
	Velocity (m/min)	150	125	90	110
Tool Life	T_{sugg} (min)	0.92	2.02	8.33	3.51
Mach. Power	P (kW)	6.84	6.36	5.76	7.04
Spindle Speed	*rpm* (rev/min)	1061.57	884.6	636.9	778.485

The calculated machine power values are higher than the previous tests but still within the machine tool's capability. These high power requirements are due to the high value of the specific resistance to cut of this material (approximately 2500 N/m^2). Spindle speeds were kept low to avoid increasing the temperature in the cutting zone. On the other hand, these tests used high values for the depth of cut and the feed rate. It can be seen from Table 5.7 that the tool life values (T_{sugg}) predicted by TLP were very low.

The flank wear characteristics with cutting time for all the TP35 indexable inserts used in these tests are shown in Figure 5.8. It can be observed that this insert grade exhibits a more or less similar wear rate pattern at different cutting conditions when cutting this material. Pictures of some inserts are shown in *Appendix 5D*.

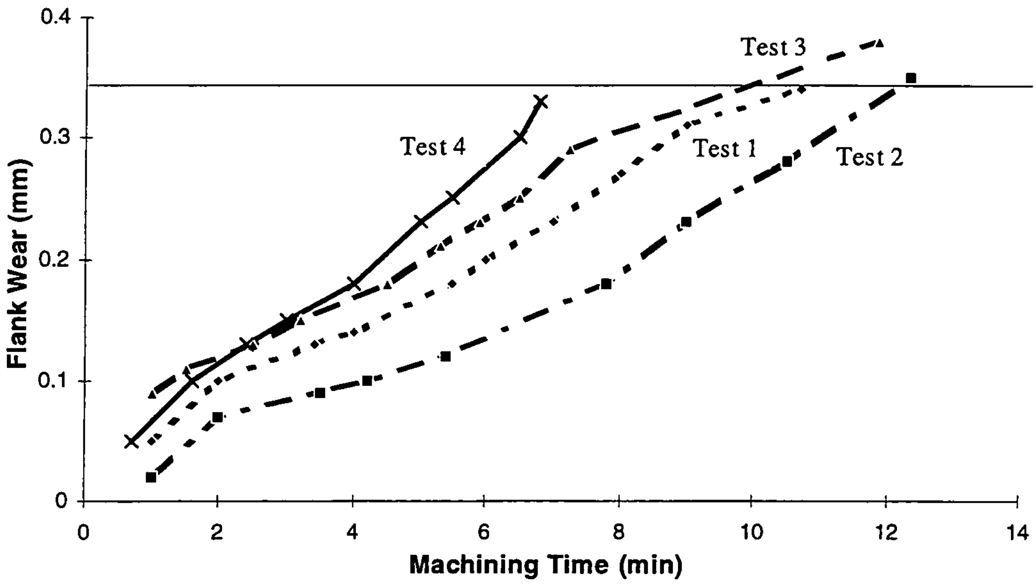

Figure 5.8 Flank wear with machining time for semi-roughing turning SS316 with TP35

The tool life values suggested by TLP and the real experimental values are shown in Table 5.8. It is clear that the theoretical tool life coefficients resulted in a serious underestimation of the tool life of this grade. This will result in high insert costs, low productivity and increased set up times. These underestimated values might be attributed to the fact that the tool manufacturer's recommendations were generalised since they were based on only 32 material sub-classes while there are about 98 material sub-classes according to the *Machining data handbook* (1980). Also, manufacturers want to be conservative in their recommendations and they usually base their cutting data for a sub-class on the worst material or material condition in terms of machinability. Hence, when an alternative material of the same sub-class is tried, the results exceed the predictions.

Table 5.8 T_{sugg} and T_{app} when semi-roughing SS316 using TP35

Test number	*Test 1*	*Test 2*	*Test 3*	*Test 4*
T_{sugg} *(min)*	0.92	2.02	8.33	3.51
T_{app} *(min)*	10.733	12.33	11.85	6.83
$\frac{T_{sugg}}{T_{appr}} \times 100$ %	8.6 %	16 %	70 %	51 %

5.4 DISCUSSION

The general result of the initial tool life tests was that it is very difficult to predict accurately tool life by using tool manufacturer's data. By comparing the tool life values suggested by the tool life prediction (TLP) module with the approved tool life values collected from the shop floor (Table 5.2, Table 5.4, Table 5.6 and Table 5.8), it is obvious that some predictions are good whilst others are completely different from the real values. The main reasons for deviations are; the use of general material sub-classes which may contain several distinct groups of materials in terms of machinability, and the use of simple empirical factors to alter cutting velocity in order to obtain increased tool life values. Therefore, there is a need to develop another method which uses dynamic multiple regression to calculate the tool life constants based on the approved data in order to supply the user with tool life values much closer to the real values collected from the shop floor. This method should be dynamic so that it can include any approved data whenever it becomes available as will be discussed in the following Chapter.

TOOL LIFE ASSESSOR

The main function of the tool life assessor (TLA) module is to employ the least squares method to provide a statistical analysis for approved tool life data under different cutting conditions in order to adjust and improve the results of the prediction module. The first task is to select an operation with a predicted tool life from the TLP session logger or from the system's database. Based on the selected operation, TLA retrieves all similar machining operations from the approved database and applies multiple regression in real time to calculate the approved tool life coefficients. The generated approved tool life coefficients are used to calculate the tool life value for the given operation. This tool life is used instead of the predicted tool life value (T_{sugg}) and is referred to as the modified tool life value (T_{mod}). This module also calculates the variance for the approved tool life data and supply the user with the 95% confidence range values associated with any modified tool life. The overall structure of the TLA module is shown in Figure 6.1.

The main objectives of the tool life assessor (TLA) module are:

- To provide a dynamic modification of tool life predictions by applying multiple regression when new approved data becomes available.

- To provide a statistical analysis of tool life over a range of cutting velocities and feed rates and over a range of wear levels when flank wear is employed as a criterion for tool life.
- To demonstrate an improvement in the accuracy of the tool life predictions when TLA is employed.

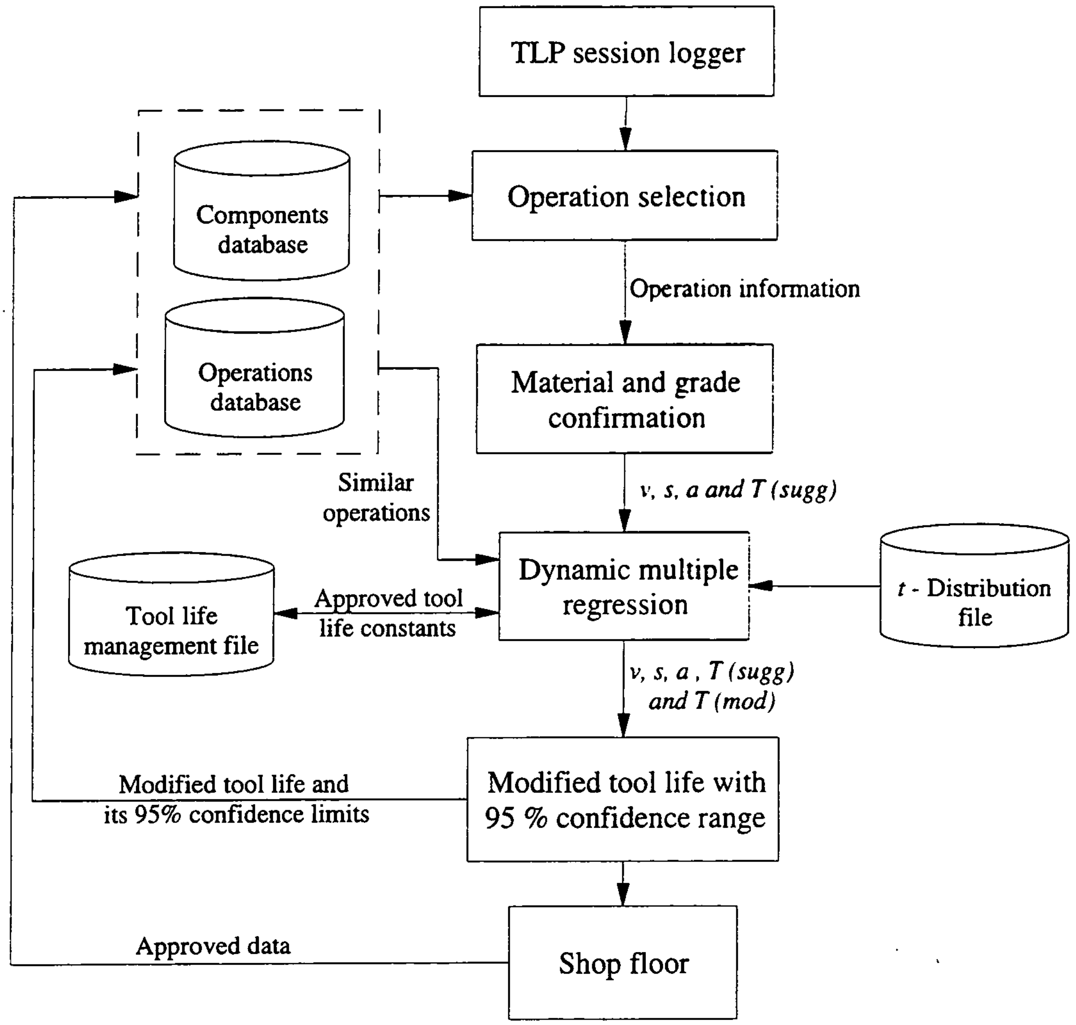

Figure 6.1 The Overall Structure of the Tool Life Assessor

6.1 TLA FUNCTIONALITY

For any selected operation, either from the TLP session logger or from the operations database, TLA retrieves all similar operations from the system's database based on the following similarity criteria:

- Same carbide insert grade (TP10, TP20 etc.)
- Same material sub-class (very soft steel, free cutting steel etc).
- Same type of cut (finishing, medium-roughing or roughing).
- Wet or dry cut.

If there is enough approved data (at least four points), TLA generates a dynamic multiple regression to calculate the approved tool life coefficients (lnC, $\frac{1}{\alpha}$, $\frac{1}{\beta}$) and the related degree of freedom ($d.o.f$).

$$d.o.f = n - p \qquad (6.1)$$

where; n is the number of the retrieved data and p is the number of parameters in the model (lnC, $\frac{1}{\alpha}$, $\frac{1}{\beta}$).

Based on the calculated degree of freedom, the associated t-distribution critical value will be retrieved from the t-distribution critical values database *(Appendix 1)* and the 95% confidence interval will be calculated.

Full job details and the modified tool life value (T_{mod}) with its 95% confidence interval are displayed on the results screen and the user is asked to confirm whether they are acceptable. If the user chooses "NO", the system will restart again showing the TLA top menu and will ask the user to select another operation. If "YES" option is selected, TLA gives the user choices for saving the operation and the modified tool life value with its 95% confidence interval in the approved database. TLA also saves the new calculated coefficients (lnC, $\frac{1}{\alpha}$, $\frac{1}{\beta}$), the associated number of points, material sub-class, insert grade and the type of cut in the management file (the structure of which will be explained fully in the next Chapter).

The 95% confidence interval of tool life values from TLA shows a good degree of confidence in approximating to the actual tool life values from the experiments. This requires a maximum variance of the predicted true mean natural logarithmic-transformed tool life $var\ [ln\hat{T}]$, where; the variance of the predicted $ln\hat{T}_*$ at cutting conditions $\mathbf{x}_*$ is:

$$var\ [\ ln\hat{T}_*\ ] = \mathbf{x}_*^{\mathbf{T}}\ [\mathbf{X}^{\mathbf{T}}\mathbf{X}]^{-1}\mathbf{x}_*\ \sigma^2 \tag{6.2}$$

where; $\mathbf{x}_*^{\mathbf{T}}$ and $\mathbf{X}^{\mathbf{T}}$ is the transpose of the matrix $\mathbf{x}_*$ and $\mathbf{X}$ respectively. Generally, the transpose of $n \times p$ matrix is a $p \times n$ matrix.

σ^2 is the variance of the lnT_i observations about the fitted line. σ^2 is usually estimated with the residual variance S^2.

$$S^2 = \frac{1}{n-p} \sum (\ lnT - \ ln\hat{T}\ )^2 \tag{6.3}$$

The method for calculating the variance will be shown in the next section.

6.2 LEAST-SQUARES METHOD

The large variation of tool life data gives rise to a high degree of uncertainty in tool life models and predicted tool life values. These levels of uncertainty make it difficult to maintain the economic optimization of the manufacturing process. Therefore, large numbers of tests are often performed to reduce this variation and this greatly increases costs. For this reason statistical techniques such as transformation and least-squares have been advocated to develop better mathematical methods to model and predict tool life. In some experimental data, logarithmically transformed tool life showed increasing variance for short tool lifetimes because of tough machining operations and cases in which the tool life failure mechanism is changing. The lack of homogeneity of variance over cutting conditions can be largely avoided by dividing the model data space into three cutting types namely, finishing, medium roughing and roughing in which the least-squares analysis can be employed with a high degree of certainty.

In multiple regression, several predictors are used to model a single response variable. For each of the *n* cases observed, values for the response and for each of the predictors are collected. If the response is called Y, and the predictors are called x_1, x_2, ..., xp (*p* is the number of predictors), then the equation that expresses the response as a linear function of the *p* predictors is estimated using the observed data. The model is expressed by a linear equation:

$$Y = b_o + b_1 x_1 + b_2 x_2 + ... + b_p x_p + \varepsilon \qquad (6.4)$$

When $p = 2$, equation 6.4 describes a two-dimensional plane in the three dimension (x_1, x_2, Y) space (tool life model).

When $p = 2$, equation 6.4 can be written as:

$$Y = b_o + b_1 x_1 + b_2 x_2 + \bar{\varepsilon} \tag{6.5}$$

The logarithmic transformation of tool life equation is of the same form as equation 6.5.

$$\hat{lnT} = \hat{lnC} + \left(-\hat{\frac{1}{\alpha}} \right) lnv + \left(-\hat{\frac{1}{\beta}} \right) lns + \varepsilon \tag{6.6}$$

where; $\hat{lnT}$ is the random variable of the logarithmically transformed tool life, v is the cutting velocity, s is the feed rate, $\hat{lnC}$, $\hat{\frac{1}{\alpha}}$ and $\hat{\frac{1}{\beta}}$ are parameters (to be estimated), and ε is the random error. Or, in matrix notation:

$$\mathbf{Y} = \mathbf{X}\,\theta + \varepsilon \tag{6.7}$$

Let $\mathbf{Y}$ and ε be $n \times 1$ vectors whose elements are given by

$$\mathbf{Y} = \begin{bmatrix} lnT_1 \\ lnT_2 \\ \vdots \\ lnT_i \end{bmatrix} \qquad \varepsilon = \begin{bmatrix} lne_1 \\ lne_2 \\ \vdots \\ lne_i \end{bmatrix} \tag{6.8}$$

Also, define θ to be the vector parameter of length 3×1, including the intercept lnC,

$$\theta = \begin{bmatrix} lnC \\ -\frac{1}{\alpha} \\ -\frac{1}{\beta} \end{bmatrix} \tag{6.9}$$

Define $\mathbf{X}$ to be $n \times 3$ matrix given by:

$$\mathbf{X} = \begin{bmatrix} 1 & lnv_1 & lns_1 \\ 1 & lnv_2 & lns_2 \\ \vdots & \vdots & \vdots \\ 1 & lnv_i & lns_i \end{bmatrix} \tag{6.10}$$

The matrix **X** gives all of the observed values of the predictors, appended to the column of *1's*. The *ith* row corresponds to values for the *ith* case in the data; the columns of **X** correspond to the different predictors.

Matrices of the form $\mathbf{X}^{\mathbf{T}}\,\mathbf{X}$ met in regression work are always symmetric [Draper and Smith 1981], that is to say that the element in the *ith* row and *jth* column is the same as the element in the *jth* row and *ith* column. Thus, the transpose of a symmetric matrix is the matrix itself. Then the symmetric inverse is:

$$(\mathbf{X}^{\mathbf{T}}\,\mathbf{X})^{-1} = \begin{bmatrix} n & \sum lnv_i & \sum lns_i \\ \sum lnv_i & \sum [lnv_i]^2 & \sum lnv_i\; lns_i \\ \sum lns_i & \sum lnv_i\; lns_i & \sum [lns_i]^2 \end{bmatrix}^{-1} = \begin{bmatrix} A & B & C \\ B & D & E \\ C & E & F \end{bmatrix}$$

where;

$$A = \left\{\sum [ln\,v_i]^2 \sum [ln\,s_i]^2 - \left[\sum ln\,v_i\; lns_i\right]^2\right\} / G$$

$$B = -\left\{\sum lnv_i \sum [lns_i]^2 - \sum ln\,s_i \sum ln\,v_i\; lns_i\right\} / G$$

$$C = \left\{\sum ln\,v_i \sum [lnv_i\; lns_i] - \sum ln\,s_i \sum [ln\,v_i]^2\right\} / G$$

$$D = \left\{n \sum [ln\,s_i]^2 - \left[\sum ln\,s_i\right]^2\right\} / G$$

$$E = -\left\{n \sum [ln\,v_i\; ln\,s_i] - \sum ln\,v_i \sum ln\,s_i\right\} / G$$

$$F = \left\{n \sum [ln\,v_i]^2 - \left[\sum ln\,v_i\right]^2\right\} / G$$

and

$$G = n \sum [lnv_i]^2 \sum [lns_i]^2 + 2 \sum lnv_i \sum lns_i \sum lnv_i \, lns_i - n [\sum lnv_i \, lns_i]^2$$

$$- [\sum lnv_i]^2 \sum [lns_i]^2 - [\sum lns_i]^2 \sum [lnv_i]^2$$

Once we have estimated θ (lnC, $\frac{1}{\alpha}$, $\frac{1}{\beta}$) from n observations of **Y**. However, in practice one is generally interested in predicting the value $ln T_*$ of the random variable **Y**, at given cutting conditions $\mathbf{x} = \mathbf{x}_*$, where;

$$\hat{lnT_*} = \mathbf{x}_* \theta + \mathbf{e}_* \tag{6.11}$$

where; $\mathbf{x}_*$ is any given cutting conditions

$$\mathbf{x}_* = \begin{bmatrix} 1 \\ lnv_* \\ lns_* \end{bmatrix} \tag{6.12}$$

The variance can be calculated as follows:

$$var [\hat{lnT_*}] = \mathbf{x}_*^{\mathbf{T}} \; var \, \hat{\theta} \; \mathbf{x}_* \tag{6.13}$$

where;

$$\mathbf{x}_*^{\mathbf{T}} = \begin{bmatrix} 1 & ln \, v_* & ln \, s_* \end{bmatrix} \tag{6.14}$$

$$var \, \hat{\theta} = [\mathbf{X}^{\mathbf{T}} \mathbf{X}]^{-1} S^2 \tag{6.15}$$

By substituting equation 6.15 into equation 6.13, the result is equation 6.2.

The modified tool life value with 95% confidence intervals is given by:

$$\hat{lnT_*} \pm t_{0.025} \sqrt{var \; [\hat{lnT_*}] + S^2} \tag{6.16}$$

Substituting equation 6.2 into equation 6.16

$$\hat{lnT_*} \pm t_{0.025} \times S\sqrt{\mathbf{1} + \mathbf{x}_*^{\mathbf{T}}\,[\mathbf{X}^{\mathbf{T}}\,\mathbf{X}\,]^{-1}\,\mathbf{x}_*} \qquad (6.17)$$

Where the degrees of freedom (*d.o.f*) for $t_{0.025}$ are the same as the devisor in calculating S^2 (see equation 6.3).

Equation 6.17 is used within the system to calculate the modified tool life value and its 95% confidence intervals for any given cutting conditions.

6.3 AN EXAMPLE

The cutting conditions and tool life values from the initial tool life tests when cutting free-cutting steels (EN8) using TP20 insert grade under semi-roughing machining conditions (Table 5.5 and Table 5.6) are logarithmically transformed to fit the linear model and are shown in Table 6.1.

Table 6.1 Cutting conditions and tool life values for TP20/EN8

T_{app} min	v m/min	s mm/rev	ln T_{app}	ln v	lns
18.80	350	0.2	2.934	5.858	- 1.609
21.32	330	0.2	3.06	5.799	- 1.609
6.700	310	0.25	1.902	5.737	- 1.386
13.13	295	0.28	2.575	5.687	- 1.273

$$\overline{lnT} = 2.618 \quad \overline{lnv} = 5.77 \quad \overline{lns} = -1.47$$

$$\sum\left(ln\,v_i - \overline{ln\,v}\right)\left(ln\,T_i - \overline{ln\,T}\right) = 0.068$$

$$\sum\left(ln\,s_i - \overline{ln\,s}\right)\left(ln\,T_i - \overline{ln\,T}\right) = -0.174$$

$$\sum\left(ln\,v_i - \overline{ln\,v}\right)^2 = 0.017$$

$$\sum\left(ln\,s_i - \overline{ln\,s}\right)^2 = 0.085$$

$$\sum\left(ln\,v_i - \overline{ln\,v}\right)\left(ln\,s_i - \overline{ln\,s}\right) = -\,0.0355$$

From multiple regression (equations 6.5 and 6.6):

$$0.0681 = (-\hat{\frac{1}{\alpha}})\,(0.0166) + (-\hat{\frac{1}{\beta}})\,(-\,0.0355) \qquad \text{(i)}$$

$$-\,0.174 = (-\hat{\frac{1}{\alpha}})\,(0.0355) + (-\hat{\frac{1}{\beta}})\,(0.0847) \qquad \text{(ii)}$$

By solving equation (i) and equation (ii)

$$\hat{\frac{1}{\beta}} = 3.2 \qquad \text{and} \qquad \hat{\frac{1}{\alpha}} = 2.74$$

From equation 4.7

$$ln\,\hat{C} = 13.72$$

Equation (4.1) can be written as:

$$ln\,\hat{T} = 13.72 - 2.74\; lnv - 3.2\; lns \qquad \text{(iii)}$$

Table 6.2, shows the tool life values (lnT_{mod}) and the associated residuals predicted by the fitted model.

Table 6.2 The natural logarithmic tool life values and their residuals

lnT_{app}	lnT_{mod}	Residuals e	e^2
2.934	3.125	−0.192	0.037
3.060	3.287	−0.227	0.052
1.902	2.744	−0.842	0.709
2.575	2.517	−0.058	0.003

Equation 6.8, 6.9 and 6.10 can be defined as:

$$\mathbf{Y} = \begin{vmatrix} 2.934 \\ 3.060 \\ 1.902 \\ 2.575 \end{vmatrix} \qquad \varepsilon = \begin{vmatrix} -0.192 \\ -0.227 \\ -0.842 \\ -0.053 \end{vmatrix} \qquad \theta = \begin{vmatrix} 13.72 \\ -2.74 \\ -3.2 \end{vmatrix}$$

$$\mathbf{X} = \begin{vmatrix} 1 & 5.858 & -1.609 \\ 1 & 5.799 & -1.609 \\ 1 & 5.737 & -1.386 \\ 1 & 5.687 & -1.273 \end{vmatrix} \qquad \mathbf{X}^{\mathbf{T}} = \begin{vmatrix} 1 & 1 & 1 & 1 \\ 5.858 & 5.799 & 5.737 & 5.687 \\ -1.609 & -1.609 & -1.386 & -1.273 \end{vmatrix}$$

Also the matrix $(\mathbf{X}^{\mathbf{T}}\,\mathbf{X})^{-1}$ can be defined as:

$$(\mathbf{X}^{\mathbf{T}}\,\mathbf{X})^{-1} = \begin{vmatrix} 4 & 23.081 & -5.877 \\ 23.081 & 133.199 & -33.947 \\ -5.877 & -33.947 & 8.719 \end{vmatrix}^{-1} = \begin{vmatrix} A & B & C \\ B & E & F \\ C & F & K \end{vmatrix}$$

$G = -7.759$

$A = -1.162$ $\qquad$ $D = -0.044$

$B = 0.225$ $\qquad$ $E = -0.018$

$C = 0.093$ $\qquad$ $F = 0.107$

Then, for any given cutting conditions $(\mathbf{x}_*)$ (say: $v = 340$ and $s = 0.2$, the predicted value

$(\widehat{lnT})$ at this cutting conditions can be calculated from equation (iii) as follows:

$$\widehat{lnT} = 2.8973$$

Also we can define $\mathbf{x}_*$ and $\mathbf{x}^{\mathbf{T}}$:

$$\mathbf{x}_* = \begin{vmatrix} 1.0 \\ 5.829 \\ -1.609 \end{vmatrix} \qquad \mathbf{x}_*^{\mathbf{T}} = \begin{vmatrix} 1.0 & 5.829 & -1.609 \end{vmatrix}$$

We can calculate $\mathbf{x}_*^{\mathbf{T}}\ (\mathbf{X}_*^{\mathbf{T}}\ \mathbf{X})^{-1}\mathbf{x}_*$ as follows:

$$= \begin{vmatrix} 1 & 5.829 & -1.609 \end{vmatrix} \begin{vmatrix} -1.162 & 0.225 & 0.093 \\ 0.225 & -0.044 & -0.018 \\ 0.093 & -0.018 & 0.107 \end{vmatrix} \begin{vmatrix} 1.0 \\ 5.829 \\ -1.609 \end{vmatrix}$$

$$= \begin{vmatrix} 0.0 & -0.0025 & -0.184 \end{vmatrix} \begin{vmatrix} 1.0 \\ 5.829 \\ -1.609 \end{vmatrix} = 0.2814$$

The variance σ^2 can be calculate as follows:

$\sigma^2 = \frac{1}{n-3}\sum e_i^2$, where n is the number of observations = 4.

$\sigma^2 = 0.800$

Equation 6.2 can be written as:

$$var[\hat{lnT_*}] = 0.284 \times 0.8$$

The 95% confidence intervals can be calculated as follows:

$$\hat{lnT} = 2.8973 \pm t_{0.025} \times 0.894 \times \sqrt{1+0.2814}$$

The degree of freedom $(d.o.f) = 4-3 = 1$

From *Appendix 1*, and at 1 degree-of-freedom $t_{0.025} = 12.7$

$$\hat{lnT} = 2.8973 \pm 12.7 \times 0.894 \times 1.1318$$

$$\hat{lnT} = 2.8973 \pm 12.84$$

TOOL LIFE MANAGEMENT

In building a reliable tool life prediction system for a real factory which consists of dozens of machines, hundreds of parts and thousands of cuts and operations every week, it is very important to establish a method of collecting and processing feedback information from cutting processes. In particular, methods were developed for analyzing, continually or at fixed intervals, the variation in the tool life data calculated by the two prediction modules (TLP and TLA) as well as the real approved results collected from the shop floor in order to provide the necessary feed back information for effective tool life control.

Tool life management (TLM), which is shown in Figure 7.1, has access to the approved operations database and the management database file in order to retrieve the tool life data suggested by the prediction and assessment modules (TLP and TLA) as well as the approved tool life data collected from the shop floor. TLM studies the variations in these retrieved data and provides feedback for the system, mainly TLA, in order to adjust and improve future prediction results. TLM is a strategic, management tool which can be used to assess the effectiveness and accuracy of tool life predictions over a long period of time. It is designed to operate within an industrial environment and for that, an appropriate interpretation of real tool life achieved is required. The measurement of the wear land and the application of formal tool life criteria may be unsustainable in most companies since they may involve extensive additional operations. Instead, the achieved, real tool life should be based on criteria presently applied by machinists such as change in chip size and shape, vibration and noise. The functions of TLM are described below.

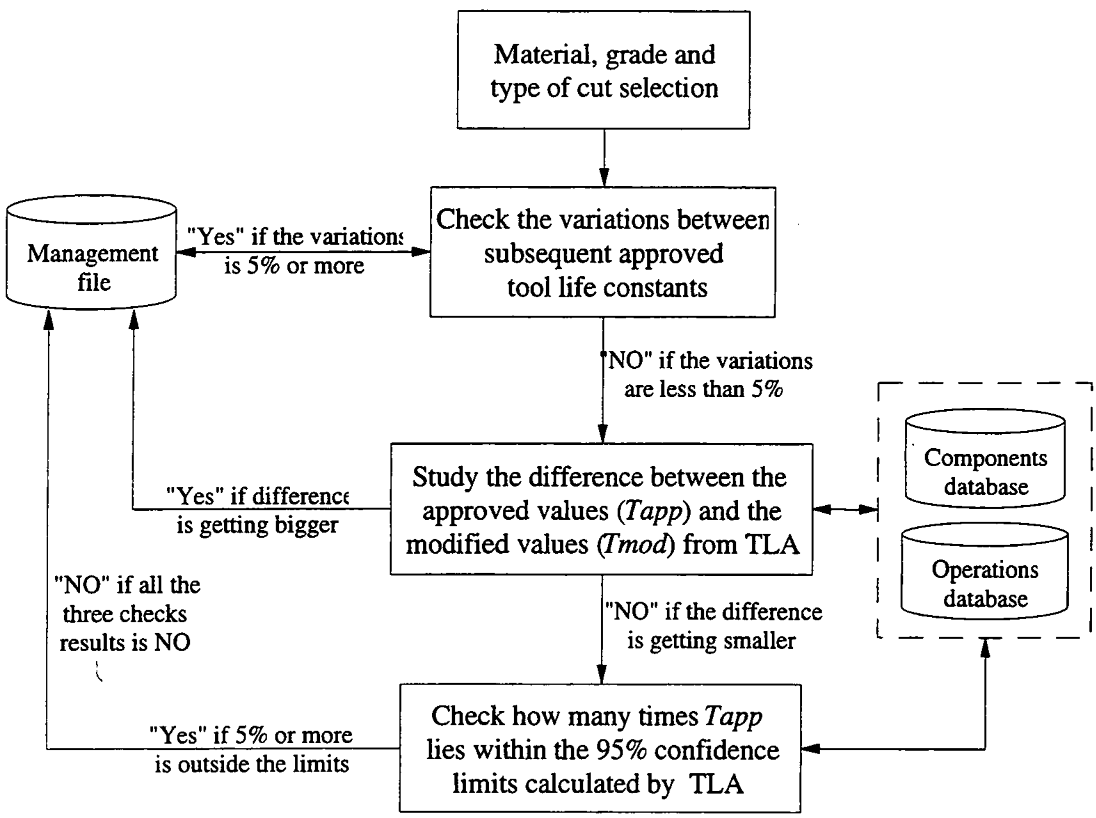

Figure 7.1 The overall structure of the tool life management

7.1 TOOL LIFE MANAGEMENT FUNCTIONALITY

For any chosen material sub-class, insert grade and type of cut, the tool life management module (TLM) retrieves tool life data from the matching operations available in the operations database and the management file database based on the following similarity criteria:

- Same material sub-class.
- Same insert grade.
- Same type of cut.
- Same cutting fluid.

For all the matching operations, TLM retrieves the suggested tool life values (T_{sugg}) calculated by TLP, and the modified tool life values (T_{mod}) with their 95% confidence limits calculated by TLA from the operations database. TLM also retrieves the real, approved tool life constants for the last two tests ($test_{n-1}$ and $test_n$) from the management file database. The management file structure is shown in Table 7.1.

Table 7.1 The management database file structure

Material sub-class	***Insert grade***	***Cut type***	***No. of points***	***ln C***	***1/α***	***1/β***	***lnC var***	***1/α var***	***1/β var***
Free cutting steel	TP10	F	*5*	lnC_1	$(1/\alpha)_1$	$(1/\beta)_1$	–	–	–
Free cutting steel	TP10	F	*10*	lnC_2	$(1/\alpha)_2$	$(1/\beta)_2$	var_1	var_1	var_1
Free cutting steel	TP10	F	*21*	lnC_3	$(1/\alpha)_3$	$(1/\beta)_3$	var_2	var_2	var_2
: :	: :	: :	: :	: :	: :	: :	: :	: :	: :
Free cutting steel	TP10	F	:	lnC_{n-1}	$(1/\alpha)_{n-1}$	$(1/\beta)_{n-1}$	var_{n-1}	var_{n-1}	var_{n-1}
Free cutting steel	TP10	F	:	lnC_n	$(1/\alpha)_n$	$(1/\beta)_n$	var_n	var_n	var_n

For any selected combination of material sub-class, insert grade and type of cut, the tool life management (TLM) module has three main functions:

- Calculates the variations between the approved tool life constants in the last two retrieved tests ($test_{n-1}$ and $test_n$).
- Calculates the difference between the approved tool life value (T_{app}) collected from the shop floor and the modified value (T_{mod}) predicted by TLA by using the approved tool life constants in the last two retrieved tests.
- For all matching operations retrieved from the operations database, TLM counts how many times (as a %) the approved tool life values lie within the 95% confidence limits calculated by TLA.

7.1.1 The variation in approved tool life constants

For this check, TLM retrieves from the management database file the tool life data in the last two approved records ($test_{n-1}$ and $test_n$) and calculates the 5% values of the variables lnC_{n-1}, $(1/\alpha)_{n-1}$ and $(1/\beta)_{n-1}$ where; $n-1$ is the observation before the last one.

TLM calculates the variations in the approved tool life constants calculated by multiple regression in the last two tests as follows:

$$var\ (ln\,C) = |\ ln\,C_n - ln\,C_{n-1}\ | \tag{7.1}$$

$$var\ (1/\alpha) = |\ (1/\alpha)_n - (1/\alpha)_{n-1}\ | \tag{7.2}$$

$$var\ (1/\beta) = |\ (1/\beta)_n - (1/\beta)_{n-1}\ | \tag{7.3}$$

Then TLM compares the variation for each constant, *var (lnC), var (1/α)* and *var (1/ β)*, with its 5% value in the (*n–1*) observation and the following conditions are checked:

- Condition 1: $var\,(lnC) \leq 5$ % of the lnC_{n-1} value
- Condition 2: $var\,(1/\alpha) \leq 5$ % of the $(1/\alpha)_{n-1}$ value
- Condition 3: $var\,(1/\beta) \leq 5$ % of the $(1/\beta)_{n-1}$ value

If any of the above conditions is not true, TLM will automatically register a "YES" option (i.e. there is a change in the new calculated constant(s) by more than 5% from the previous calculated one). Otherwise, the "NO" option will be registered since there is no significant change between the constant(s) calculated in $test_{n-1}$ and the tool life constant(s) calculated in $test_n$ as a result of performing more tests. The user is allowed to set any other limit in the variation allowed.

This function aims to record and study the variations in tool life constants calculated by TLA as a result of adding more approved results. It is expected that initially there will be wider variations in the tool life coefficients and subsequently these variations will be reduced as a result of calculating the values by using more approved tests.

7.1.2 The difference between T_{app} and T_{mod}

For the chosen material sub-class, insert grade and type of cut, TLM retrieves the approved tool life values collected from the shop floor (T_{app}) and the last two modified tool life values (T_{mod}) predicted by TLA. TLM calculates the difference between the successive T_{app} and T_{mod} sets and the following condition is checked:

- <u>*Condition 4:*</u> $\left|T_{app} - T_{mod}\right|_{test\ n} \leq \left|T_{app} - T_{mod}\right|_{test\ n-1}$

If the above test is true, TLM registers a "NO" option to indicate that the difference between the approved and modified values in the last test ($test_n$) is smaller than the difference in the previous test ($test_{n-1}$). Otherwise, a "YES" option is registered to indicate that the difference is getting bigger. Of course, if this happens it means that the predictions have not reached a stable point and the particular set of approved results cannot guarantee the accuracy of predictions.

7.1.3 The approved tool life and the boundary limits from TLA

For the given combination of material sub-class, insert grade, type of cut and cutting fluid, TLM retrieves from the operations database the approved tool life values collected from the shop floor and the modified tool life values with their 95% confidence intervals as calculated by TLA. TLM counts how many times (%) the approved values lie within the boundary limits calculated by TLA.

If 95% or more of the real tool life values lie within the boundary limits set by TLA, TLM registers a "NO" option (i.e., the large majority of points are within the boundary limits). Otherwise, a "YES" is registered (i.e., more than 5% of the approved tool life values lie outside the boundary limits given by TLA). This check is very important because it shows the accuracy of the system in predicting an interval for each modified tool life value, with 95% confidence that the approved value will be within this boundary.

Finally, TLM will consider that no changes have been registered if the results from the previous three checks described in sections 7.1.1, 7.1.2 and 7.1.3 are "NO". This indicates that the newly added approved points do not affect the prediction results and the tool life constants ($ln\, C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$) calculated by TLA are considered to be stable. If this is the case, TLM advises the user to stop recording any additional approved points for the particular combination of material, grade and operation. The user is advised to use the last calculated tool life constants for future predictions.

On the other hand, TLM considers that there were noticeable changes as a result of collecting the last real data, if any of the previous three checks results in "YES". This means that the extra approved point improved the prediction results and the approved tool life constants are not final. The user is advised to keep recording additional approved points in order to improve further the predictions for the given combination. The full detailed calculations of this analysis will be given in Chapter 8.

Chapter 8

EXPERIMENTAL PHASE AND CLOSED LOOP SYSTEM

The main objectives of this testing phase were to check the functionality, validate the operation, and verify the empirical rules and criteria for each module (TPO, TLP, TLA and TLM). Another objective was to fine-tune the operation of the complete tool life control system.

8.1 OVERALL EXPERIMENTAL METHOD

In order to derive any realistic conclusions regarding functionality, these tests were conducted under the same conditions as the first testing phase. This meant that the machine tool (CNC-1000), workpiece material sub-classes (EN8 and SS316), tool holder (PCLNR2020_12A), insert grades (TP10, TP20 and TP35) and the overall testing set up were the same as in the initial testing phase. A detailed method was described in Chapter 3 for calculating the machining constraints for a given set of cutting conditions (v, s and a), to make sure that the cutting data will work on the lathe the first time around.

From the definition given in Chapter 6, TLA needs at least four approved points to generate a dynamic regression and calculate the tool life constants ($ln\,C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$).

This is used to predict the next operation tool life value with its 95% confidence interval for any given combination of cutting data. Using the four previous approved points from the initial tool life tests, TLA calculates the modified tool life (T_{mod}) and its 95% confidence limits for the fifth operation generated by TPO. This modified tool life value was then tried on the shop floor and the approved value (T_{app}) was collected and added to the previous four approved points. In the next operation, TLA considers the five points when calculating the modified tool life value for the sixth operation.

The process described above was repeated; five times when machining free-cutting steel (EN8) with a TP10 insert grade under finish turning conditions (see Table 8.1), five times when cutting free-cutting steel under finish machining conditions using a TP20 insert grade (see Table 8.2), five times for the same material sub-class under semi-roughing machining conditions using a TP20 insert grade (see Table 8.3), and four times when using a TP35 insert grade to cut difficult stainless steel (316) under semi-roughing cutting conditions (see Table 8.4). Each time the values of $\ln C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$ and the number of the approved points upon which the calculation was based were saved in the management file. TLA also saved the modified tool life value with its 95% confidence limit for each operation into the operations data base to be considered by the TLM module.

This testing phase includes 10 finishing cuts for free-cutting steel material (EN8) with two carbide grades (TP10 and TP20), 5 semi-roughing cuts for free-cutting steel using

TP20 insert grade and 5 semi-roughing cuts for difficult stainless steel material (316) using TP35 carbide grades.

8.1.1 Results from machining free cutting (EN8) steel with TP10 insert grade

This set of tool life observations was obtained by cutting free cutting steel (EN8) with TP10 insert grade under finish-machining conditions. The initial cutting conditions used in this set were calculated by TPO module and are shown in Table 8.1. The suggested tool life values (T_{sugg}) calculated by TLP using the theoretical constants, and the modified tool life values (T_{mod}) predicted by TLA using the approved constants are also shown in Table 8.1. Table 8.1 shows that the modified values for tests 2 and 5 are considerably different from the approved values. This can be attributed to the stochastic nature of tool life and to the fact that those predictions were based on a limited number of approved points. The predictions will be improved when more approved data becomes available. On the other hand, the other three tests showed a good correlation between predictions and approved values.

The surface roughness (R_a) for these tests varied between 1.2 to 2.3 μm in order to keep the surface roughness within limits normally associated with finishing cuts.

Table 8.1 Finish machining conditions of EN8 free-cutting steel with TP10 insert grade.

Machine Tool		CNC-1000				
Tool Holder		PCLNR2020_12A				
Insert Type		CNMG120408_MF2				
Insert Grade		TP10				
Workpiece Dimension		Length=200 mm and Diameter=100 mm				
Cutting Fluid		Rocol-Ultracut 370				
	Test No.	*Test 1*	*Test 2*	*Test 3*	*Test 4*	*Test 5*
Cutting Parameters	Depth (mm)	1.5	0.5	1.4	0.8	1.5
	Feed (mm/rev)	0.18	0.24	0.17	0.22	0.18
	Velocity (m/min)	450	490	405	410	430
Tool Life	T_{sugg} (min)	8.99	5.59	14.82	12.98	11.07
	T_{mod} (min)	8.69	4.61	13.77	12.02	11.14
	T_{app} (min)	8.0	8.4	12.02	13.07	8.52
Surface Roug.	R_a (μm)	1.3	2.3	1.2	1.9	1.3

Figure 8.1 shows the tool flank wear measurements with machining time for this series of tests. The average flank wear on the cutting edge is almost 0.05 mm after about 3 min of cutting in all these tests. Pictures of some inserts employed in this set of tests are shown in *Appendix 6A*.

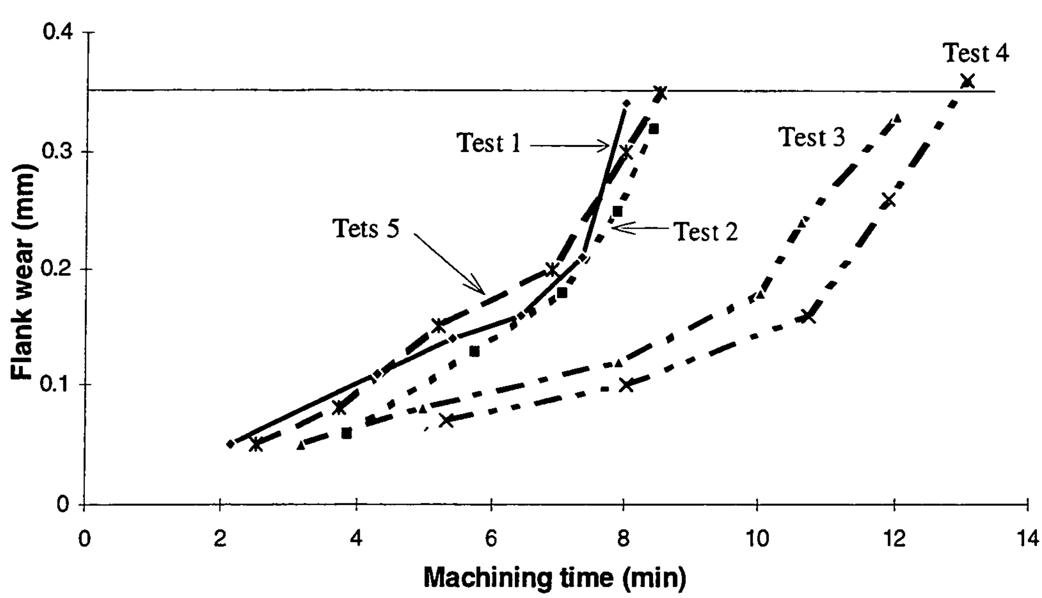

Figure 8.1. Flank wear versus machining time for finishing EN8 with TP10

Figure 8.2 shows the comparison of the three tool life values (T_{sugg} , T_{mod} and T_{app}) for the above five observations. In test 1 and 3 it is clear that the modified tool life is getting closer to what actually achieved in the experiment. In test 5 the two predicted values are very close together and the actual tool life was slightly smaller. The hypothesis that a modification of tool life will bring it closer to the experimental value is not directly proven by tests 2 and 4. Variation in set-up conditions, vibration and the randomness of tool life are the main reasons for this behaviour and it is expected that additional real values will improve future predictions.

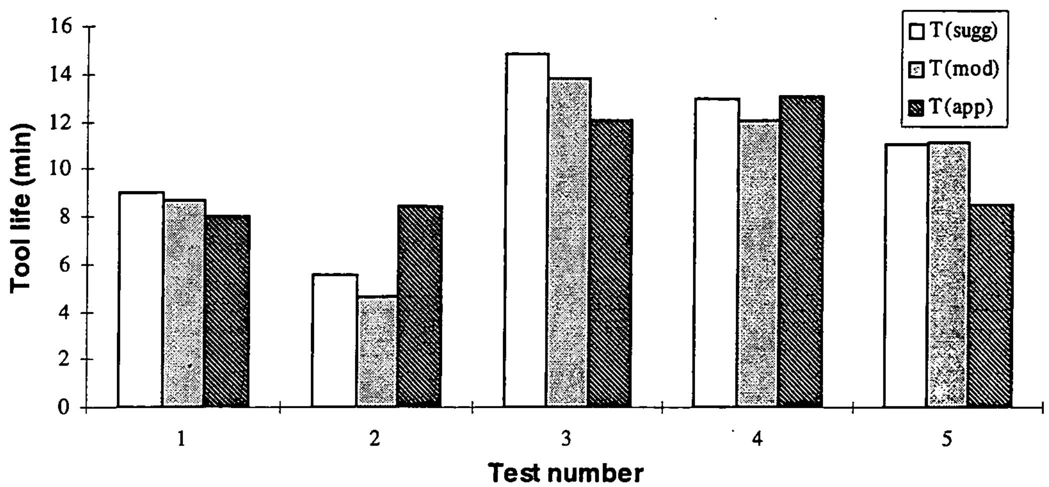

Figure 8.2 Tool life values for five TP10 inserts when finishing EN8

Figure 8.3, shows the approved tool life values and the 95% boundary limits of the T_{mod} values predicted by TLA. It can be seen that the approved tool life values in tests 2, 3, 4 and 5 were outside the confidence limits calculated by TLA. For test 2, the predicted limits were based on just 5 approved points. In test 3, the predicted modified value was based on 6 approved points and the lower limit predicted by TLA is higher than the T_{app} by approximately 1 min. In test 5, the modified value was based on 8 approved points and the lower limit is higher than T_{app} by approximately 2 min. However, the modified values for these tests were much closer to the approved values than the suggested values calculated by TLP based on theoretical tool life constants. These results show that the 95% confidence limit is not met in most cases using this set of approved data. Clearly, additional tests are needed to satisfy this tight confidence limit. However, test 3 and 4 would have satisfied a less light confidence limit.

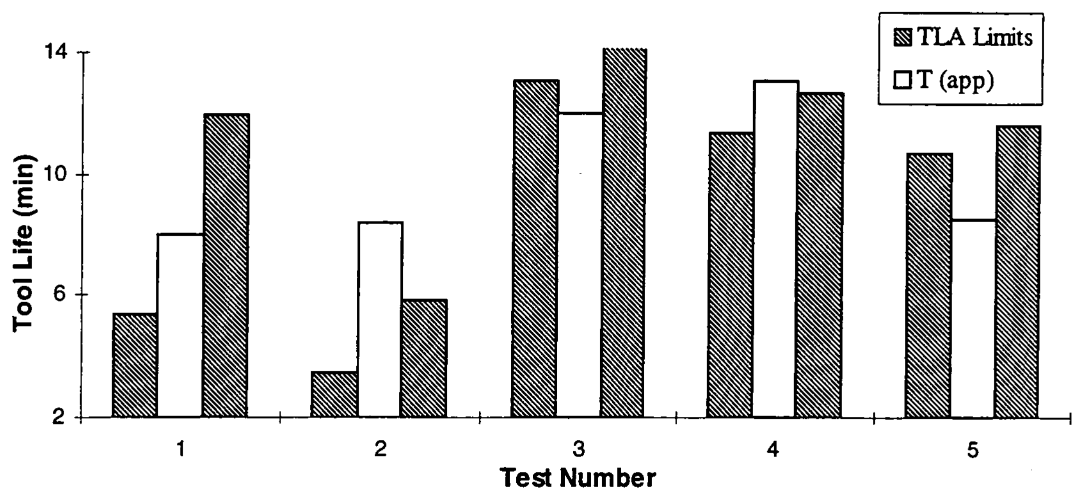

Figure 8.3 Real tool life values and boundary limits calculated by TLA

8.1.2 Results from machining free cutting steel (EN8) with TP20 insert grade

The second and third sets of 5 experiments correspond to cutting EN8 steel with a TP20 insert grade under finish and medium-roughing machining conditions respectively.

Table 8.2 shows the theoretical cutting conditions calculated by TPO and employed for five tests when finish machining EN8 free cutting steel with a TP20 insert grade. The tool life value calculated by TLP (T_{sugg}) and the modified value (T_{mod}) predicted by TLA for each set of cutting condition are also shown in Table 8.2. It is obvious that the TLA predictions were very close to the real values collected from the shop floor. The surface finish varied between 1.2 to 2.3 μm.

Table 8.2 Finish machining conditions of EN8 free-cutting steel with TP20 grade.

Machine Tool		CNC-1000				
Tool Holder		PCLNR2020_12A				
Insert Type		CNMG120408_MF2				
Insert Grade		TP20				
Workpiece Dimension		Length=200 mm and Diameter=100 mm				
Cutting Fluid		Rocol-Ultracut 370				
	Test No.	*Test 1*	*Test 2*	*Test 3*	*Test 4*	*Test 5*
Cutting Parameters	Depth (mm)	0.50	1.20	1.40	0.90	0.80
	Feed (mm/rev)	0.24	0.18	0.17	0.21	0.22
	Velocity (m/min)	470	380	360	410	430
Tool Life	T_{sugg} (min)	3.04	8.82	11.50	5.94	4.70
	T_{mod} (mm)	3.04	10.87	13.13	7.31	6.15
	T_{app} (min)	4.90	10.05	13.07	8.58	6.47
Surface Roug.	R_a (μm)	2.3	1.3	1.2	1.8	1.9

The wear rates versus machining time for the five TP20 inserts of this series of tests are plotted in Figure 8.4. It can be observed that the TP20 inserts exhibit a wide range of wear patterns when cutting EN8 free-cutting steel at this range of cutting conditions. Pictures of some TP20 inserts used in theses tests are shown in *Appendix 6B*.

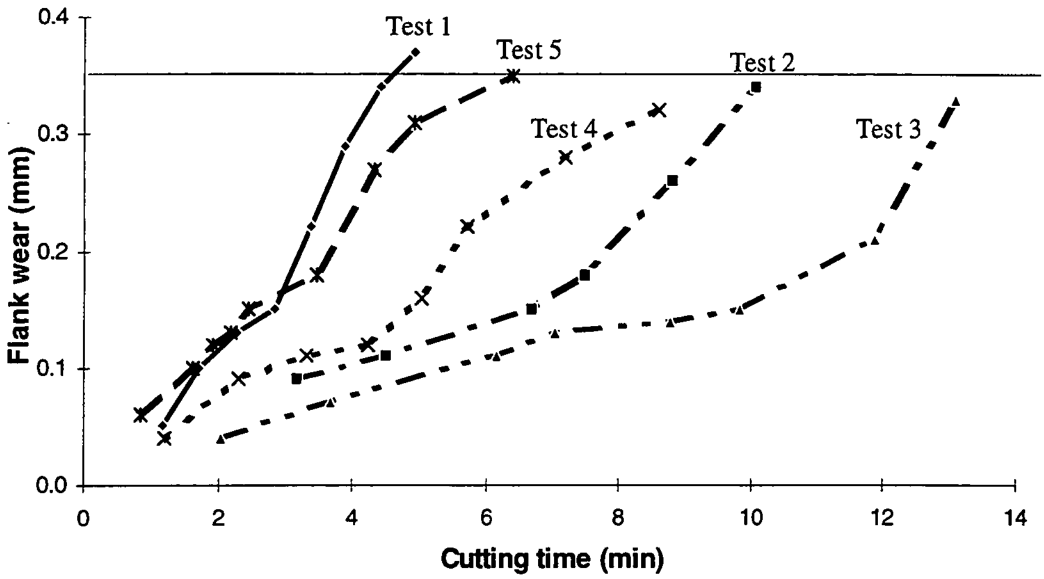

Figure 8.4 Flank wear versus machining time when finishing EN8 with TP20

Figure 8.5 shows the system's tool life predictions and the real observed values when finishing EN8 using the TP20 insert grade. It is obvious that the modified values were much closer to the real values than the original values calculated by TLP in test 2, 3, 4 and 5. Clearly, for this series of tests the modification of tool life (T_{mod}) brought the initial prediction (T_{sugg}) closer to what is actually achieved (T_{app}). These results prove the essential hypothesis of using approved data to modify theoretical tool life predictions.

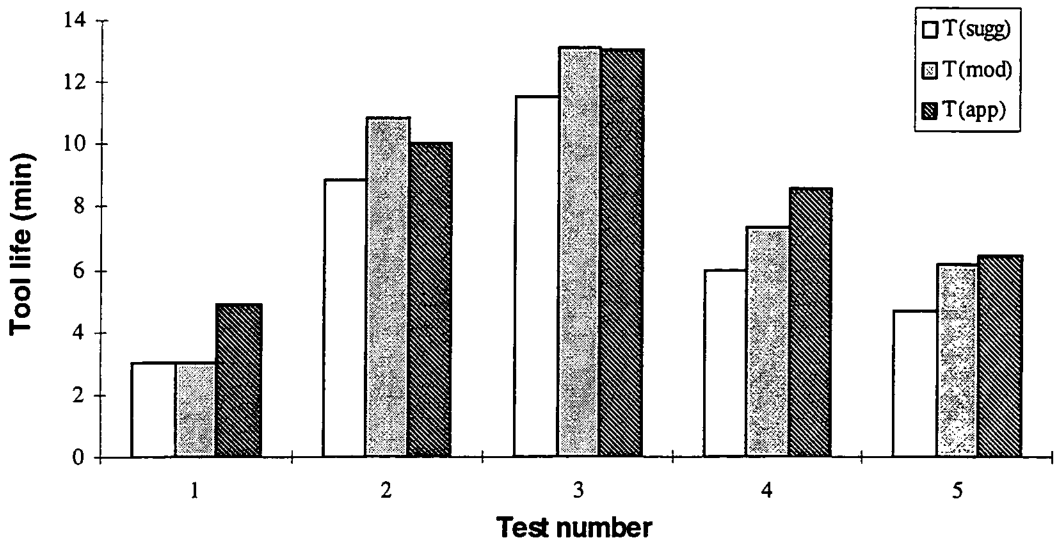

Figure 8.5 Tool life values for five TP20 inserts when finishing EN8

The calculated confidence limits for these tests are shown in Figure 8.6. It can be seen that all the approved values lie within the confidence range of T_{mod} except for the fourth test. In test 4, the upper limit predicted by TLA was based on 7 approved points and was less than T_{app} by approximately 0.376 min. In test 1, the lower limit is not shown in Figure 8.6 because it is less than zero.

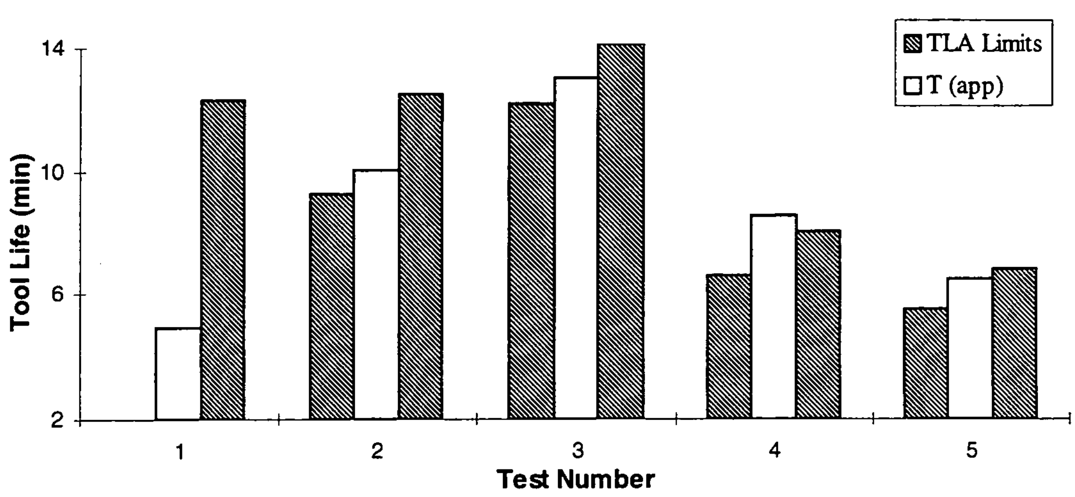

Figure 8.6 Real tool life values and boundary limits calculated by TLA

Table 8.3 shows the calculated cutting conditions and the predicted tool life values for five observations when machining EN8 free-cutting steel using TP20 carbide grade under medium-roughing machining conditions. The machine power is approximately 5 kW for all tests and this is close to the maximum power of the lathe for prolonged operation.

It can clearly be seen that the initial tool life predictions (T_{sugg}) are considerably higher than the real values (T_{app}). The theoretical tool life constants would result in unexpected, premature tool failure with catastrophic consequences. On the other hand the tool life constants calculated by using approved data is giving results (T_{mod}) which are very close to the obtained values in tests 1, 4, and 5.

Table 8.3 Semi-roughing machining conditions of EN8 steel with TP20 grade.

Machine Tool		CNC-1000				
Tool Holder		PCLNR2020_12A				
Insert Type		CNMG120408_MF3				
Insert Grade		TP20				
Workpiece Dimension		Length=200 mm and Diameter=100 mm				
Cutting Fluid		Rocol-Ultracut 370				
Cutting Parameters	*Test No.*	***Test 1***	***Test 2***	***Test 3***	***Test 4***	***Test 5***
	Depth (mm)	2.0	1.9	1.7	1.6	1.8
	Feed (mm/rev)	0.2	0.23	0.26	0.27	0.24
	Velocity (m/min)	340	320	305	300	315
Tool Life	T_{sugg} (min)	29.0	26.55	24.01	23.46	25.53
	T_{mod} (min)	18.26	13.93	9.45	9.18	11.74
	T_{app} (min)	19.45	7.8	11.17	9.13	11.05
Mach. Power	P (kW)	5.53	5.5	5.123	4.75	5.17
Spindle Speed	*rpm* (rev/min)	1804.67	1643.72	1471.72	1405.02	1567.48

Figure 8.7 shows the wear measurements along the flank face of the tool as a function of machining time for this set of experiments. Again, pictures of some inserts used in this set of tests are shown in *Appendix 6C*.

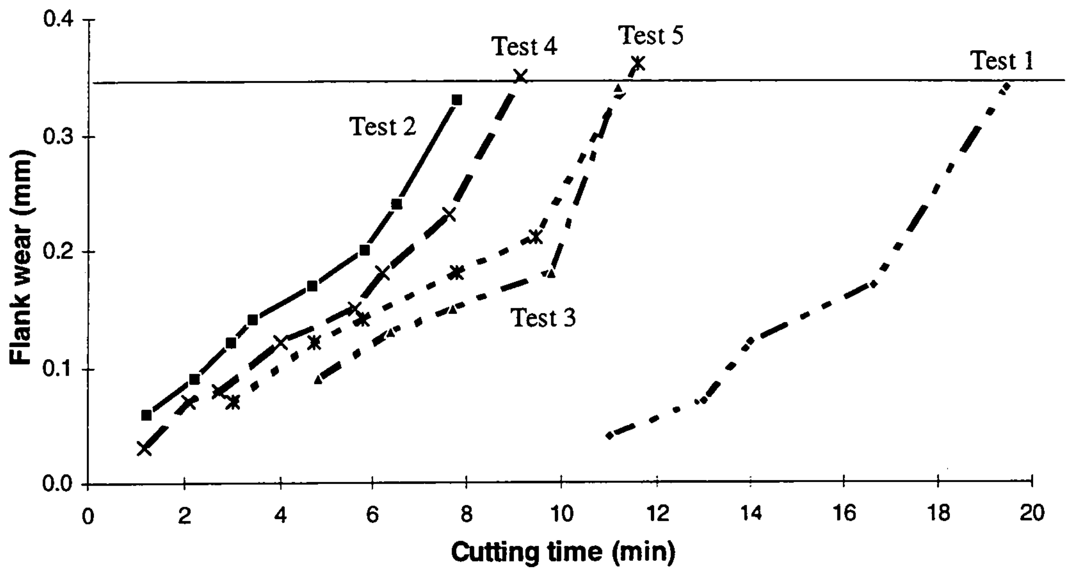

Figure 8.7 Flank wear versus machining time when semi-roughing EN8 with TP20

Figure 8.8 shows the improvements in the system's predictions when the modified values (T_{mod}) from TLA are considered. For all tests the modified values are closer to the real approved values than the initial ones as discussed above. This set of tests validates the use of real data in a closed-loop tool life prediction system.

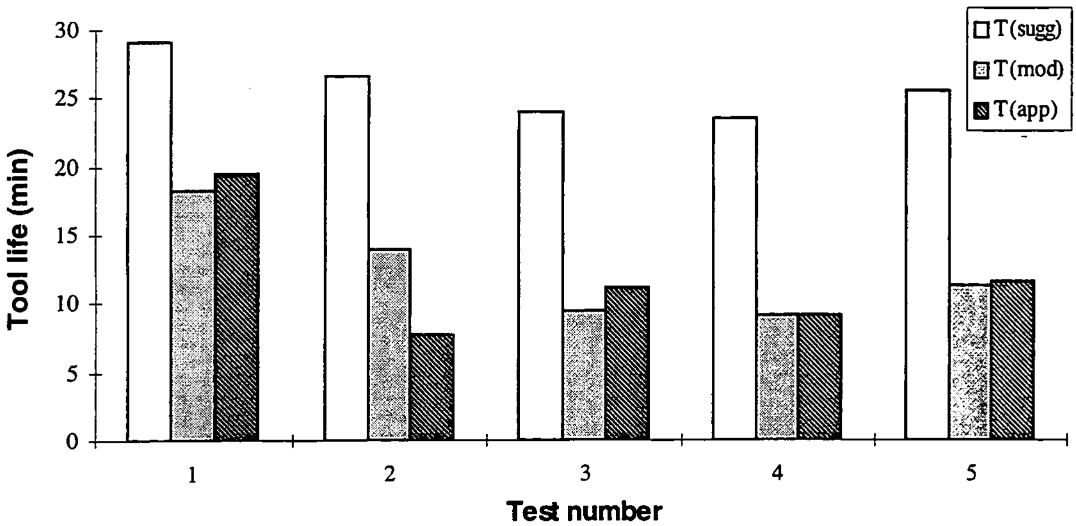

Figure 8.8 Tool life values for five TP20 inserts when semi-roughing EN8

Figure 8.9 shows the approved tool life (T_{app}) values and the boundary limits of T_{mod} calculated by TLA. It is clear that the approved values lie within the TLA boundary ranges in tests 1, 4 and 5. Test 3 is a marginal failure and test 2 is a failure.

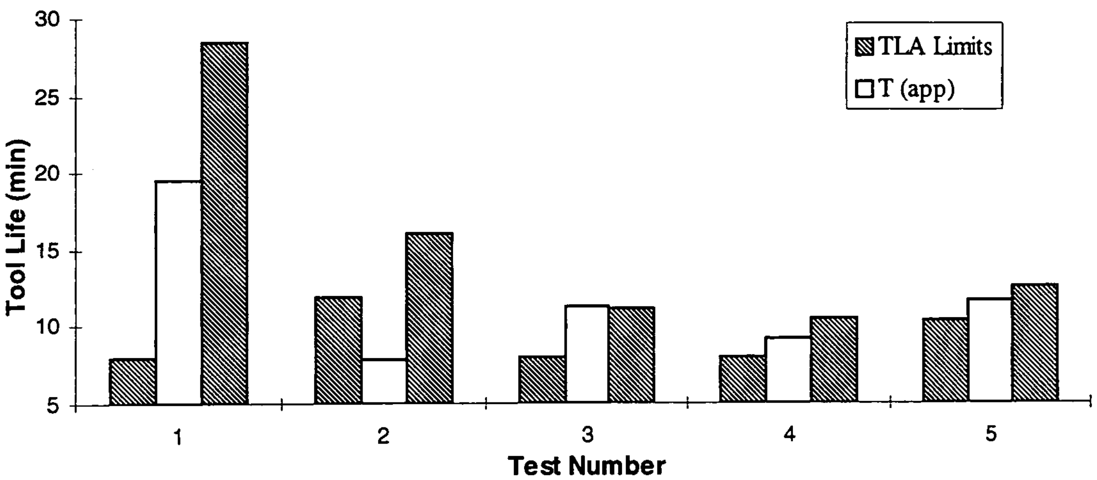

Figure 8.9 Real tool life values and boundary limits calculated by TLA

8.1.3 Results from machining difficult stainless steel 316 with TP35 insert grade

AISI 316 austenitic stainless steel is a difficult material to machine. Even when using low cutting velocity, BUE formation occurs and severe adhesive wear is readily initiated [Soderberg 1981; Soderberg 1983]. In addition, segmented chip formation occurs readily and edge chipping is often a great problem [Soderberg 1981].

Table 8.4, shows the medium-roughing machining conditions calculated by TPO and employed for 4 observations to cut difficult to machine stainless steel material (SS316) with a TP35 insert grade. The tool life values suggested by the system (T_{sugg} and T_{mod}) and the approved values (T_{app}) are also shown in Table 8.4.

The calculated power values were close to the maximum 7.5 kW, for a 30-minute operation of the lathe used. The cutting velocities employed for these tests are within the range of tool manufacturer's recommendations and result in low spindle speeds.

Table 8.4 shows that the tool life predictions using catalogue data (T_{sugg}) result in a serious underestimation of tool life. The approved results create a completely different regression curve using TLA, which modifies the suggested tool life to get closer to results obtained from the tests. These tests also validate the hypotheses that theoretical calculations may be widely inaccurate and that use of dynamic regression can improve the accuracy of tool life prediction.

Table 8.4 Semi-roughing conditions of SS316 stainless steel with TP35 grade

Machine Tool		CNC-1000			
Tool Holder		PCLNR2020_12A			
Insert Type		CNMG120404_MF3			
Insert Grade		TP35			
Workpiece Dimension		Length=200 mm and Diameter=75 mm			
Cutting Fluid		Rocol-Ultracut 370			
	Test No.	*Test 1*	*Test 2*	*Test 3*	*Test 4*
Cutting Parameters	Depth (mm)	3.0	3.0	3.0	3.0
	Feed (mm/rev)	0.3	0.25	0.4	0.3
	Velocity (m/min)	140	120	100	135
Tool Life	T_{sugg} (min)	1.24	2.40	5.29	1.45
	T_{mod} (min)	8.09	23.43	8.82	8.22
	T_{app} (min)	6.30	23.70	8.45	8.32
Mach. Power	P (kW)	7.12	5.472	6.4	6.87
Spindle Speed	*rpm* (rev/min)	990.79	849.25	707.7	955.4

Figure 8.10 shows the growth of the width of the flank wear as a function of machining time for the group of TP35 inserts. These results confirm the characteristics of the flank wear with machining time shown in the initial testing phase (see Figure 5.8). Pictures of some inserts employed in this set of tests are shown in *Appendix 6D*.

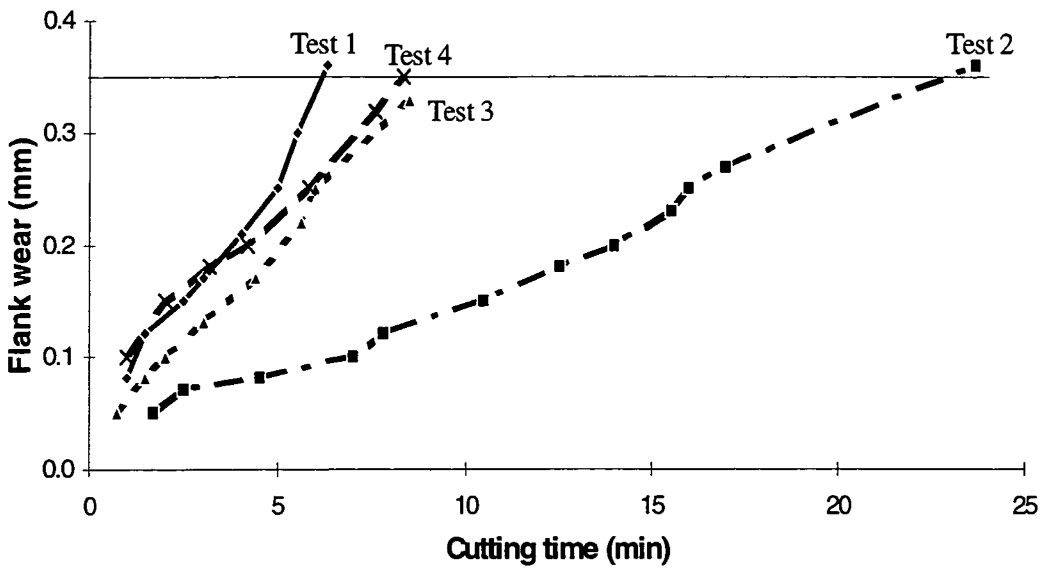

Figure 8.10 Flank wear versus machining time when semi-roughing SS316 with TP35

The three tool life values (T_{sugg}, T_{mod} and T_{app}) for the four TP35 inserts used in the tests are plotted in Figure 8.11. It can seen that the modified values (T_{mod}) from TLA were very close or even identical to the approved values observed.

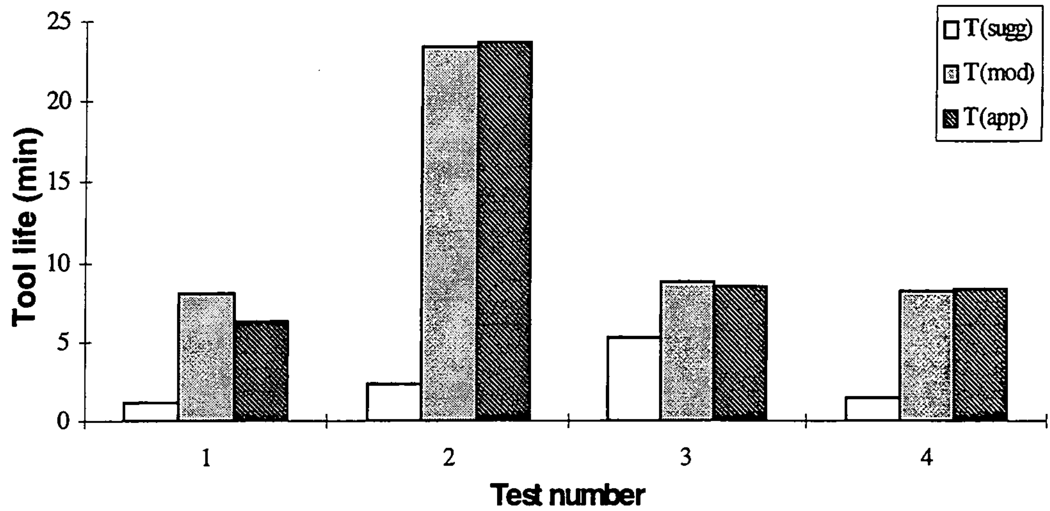

Figure 8.11 Tool life values for four TP35 inserts when semi-roughing SS316

Figure 8.12 shows the 95% confidence limits of T_{mod} and the approved values for the four TP35 inserts employed for these tests. All the approved values lie within the boundary limits predicted by TLA. This proves that a tight confidence limit is feasible when predictions are based on an adequate number of approved points.

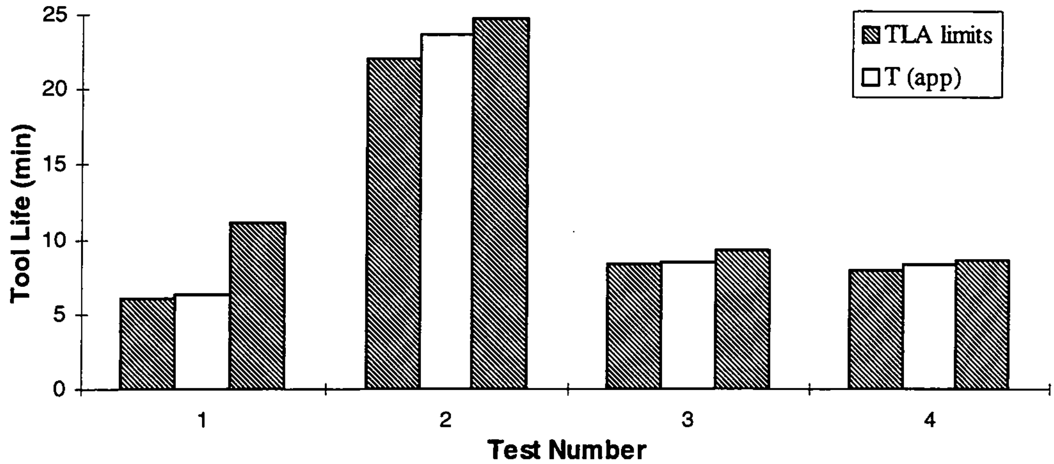

Figure 8.12 Real tool life values and boundary limits calculated by TLA

8.2 RESULTS FROM TESTING TLM

As discussed in Chapter 7, for any selected combination of material sub-class, insert grade and type of cut, TLM has three main functions:

- Study the variations in the approved tool life constants ($ln\,C$, $\frac{1}{\alpha}$, $\frac{1}{\beta}$) when new approved data becomes available.
- Study the difference between the approved tool life values (T_{app}) and the modified values (T_{mod}) predicted by TLA.
- Study how many times the approved values (T_{app}) lie within the 95% confidence limits calculated by TLA.

8.2.1 TLM results when finishing EN8 free cutting steel using TP10 insert grade

- ***Variations in tool life constants***

TLM retrieves from the management file the last two sets of the approved tool life constants $(ln\,C_{n-1}, (\frac{1}{\alpha})_{n-1}, (\frac{1}{\beta})_{n-1})$ and $(ln\,C_n, (\frac{1}{\alpha})_n, (\frac{1}{\beta})_n)$ calculated by TLA as shown in Table 8.5.

Table 8.5 Management file when finish machining EN8 using TP10 insert grade

Material sub-class	*Insert grade*	*No. of points*	*Cut type*	*lnC*	$1/\alpha$	$1/\beta$	*lnC var*	$(1/\alpha)$ *var*	$(1/\beta)$ *var*
free-cutting steel	TP10	7	F	19.001	2.801	0.223			
free-cutting steel	TP10	8	F	19.891	2.935	0.184	0.8896	0.1335	0.0394

For the $ln\,C_{n-1}, (\frac{1}{\alpha})_{n-1}$ and $(\frac{1}{\beta})_{n-1}$, TLM calculates the 5% values which are 0.95005, 0.14005, and 0.01127 respectively. TLM calculates the variations in the approved constants between $(n-1)$ and (n) set as shown in Table 8.5.

TLM compares the absolute values of the variations in the approved tool life constants with their 5% value. If a variation is larger than the 5% value, a noticeable change of constants is registered (the result of this test is YES). This is the case herein since the variation in $(1/\beta)$ value is greater than its 5% value (i.e., 0.0394 > 0.01127).

The variation in the tool life constants when adding new approved points during the machining of EN8 free cutting steel using the TP10 grade is shown in Figure 8.13. It is quite obvious that the variations in the three constants are getting smaller after the first two tests. The trend shown in Figure 8.13 shows that the tool life coefficients become more stable as more test results are considered for their calculation. This consolidation effect is important since it can allow the consolidation of one set of tool life coefficients and the termination of the need to continuously collect approved values.

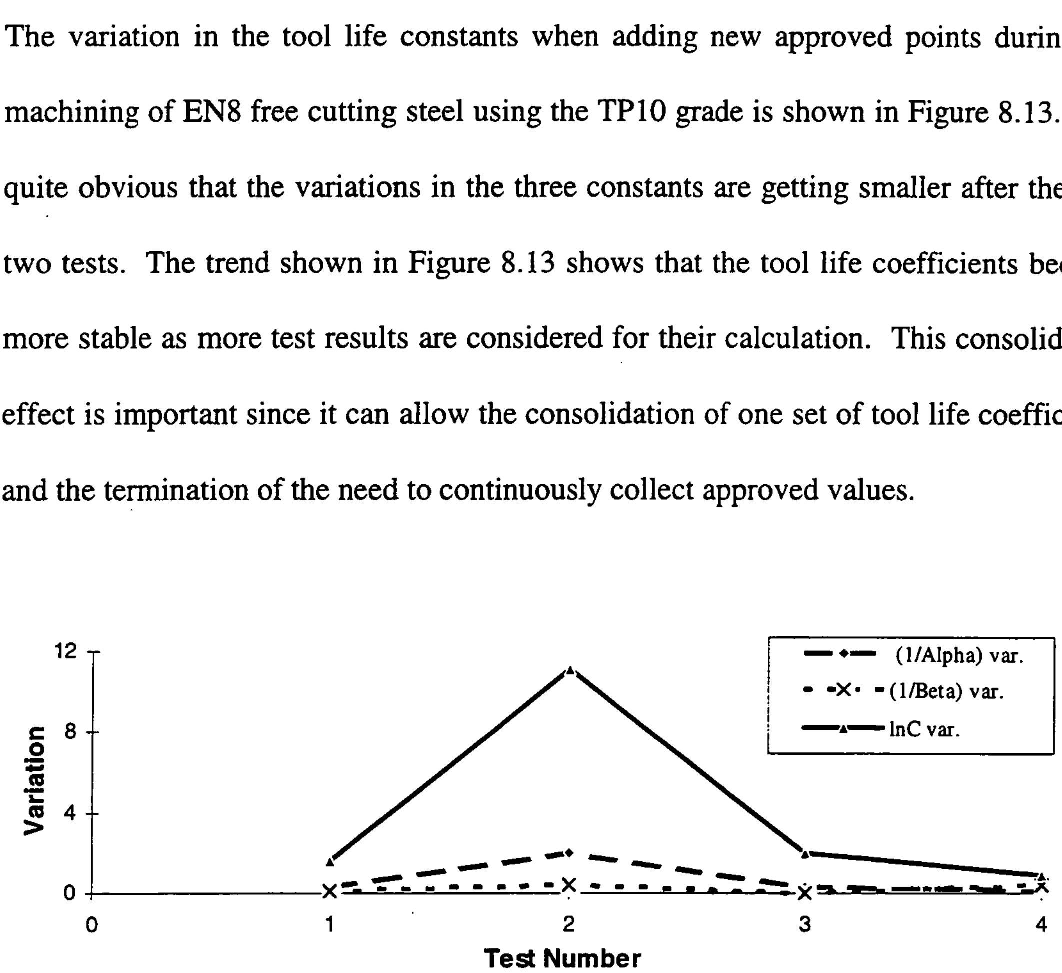

Figure 8.13 Variation in tool life constants when finishing EN8 using TP10

- ***The difference between T_{app} and T_{mod}***

From the operations database, TLM retrieves T_{app} and T_{mod} (predicted by TLA) for the last two tests (test$_{n-1}$ and test$_n$). These values were shown in Table 8.1 when finish machining EN8 using TP10 insert grade. TLM calculates the following:

$$\left|T_{mod} - T_{app}\right|_{test4} = |12.02 - 13.07| = 1.05$$

and

$$\left|T_{mod} - T_{app}\right|_{test5} = |11.14 - 8.5| = 2.64$$

TLM checks if

$$\left|T_{mod} - T_{app}\right|_{test\ n} < \left|T_{mod} - T_{app}\right|_{test\ n-1}$$

This condition means that the modified value predicted by TLA in the last test is closer to its observed value than in the previous test. In this example, this condition is not true (*2.64* > *1.05*) and the fact that there is no reduction in the variation is registered (again the result of this check is YES).

- ***T_{app} and the boundary limits calculated by TLA***

When finish machining EN8 using the TP10 insert grade, TLM retrieves the approved tool life values and the boundary limits of T_{mod} predicted by TLA from the operations database. Table 8.6 shows these values.

Table 8.6 T_{app} and T_{mod} with its 95 % confidence limits

Test no.	T_{app}	T_{mod}	*± limits*	*In*	*Out*
1	8.00	8.69	±3.295	×	
2	8.40	4.61	±1.189		×
3	12.02	13.77	±0.704		×
4	13.07	12.02	±0.674		×
5	8.52	11.14	±0.466		×

TLM checks how many times the approved tool life value collected from the shop floor lies within the boundary limits calculated by TLA as shown in Figure 8.3 and Table 8.6. If 95% or more lie within the boundary limits it is considered that the real values are effectively within the confidence limits. Otherwise, the fact that there is a violation of this check is registered and the tool life prediction set is not considered stable. This is the case in this example since tests 2, 3, 4 and 5 failed the check (80 % of the approved tool life values are outside the boundary limits). As explained in Chapter 7, a "YES" result is returned for this check.

Finally, TLM considers that the approved tool life coefficients for finish machining EN8 free cutting steel using the TP10 insert grade are not stable because the three previous checks resulted in "YES". The system will keep recording additional approved points for this combination in order to improve future predictions. The recording of additional approved points will cease when the three checks result in "negative" answers i.e., no noticeable variation in the measured parameters is registered.

8.2.2 TLM results when finishing EN8 free cutting steel using TP20 insert grade

- ***Variations in tool life constants***

Table 8.7 shows the retrieved information when finish machining EN8 steel using the TP20 insert grade.

Table 8.7 Management file when finish machining EN8 using TP20 insert grade

Material sub-class	*Insert grade*	*No. of points*	*Cut type*	*lnC*	$1/\alpha$	$1/\beta$	*lnC var*	$(1/\alpha)$ *var*	$(1/\beta)$ *var*
free-cutting steel	TP20	7	F	23.275	3.666	0.492			
free-cutting steel	TP20	8	F	22.938	3.608	0.499	0.337	0.0578	0.0064

For the lnC_{n-1}, $(1/\alpha)_{n-1}$ and $(1/\beta)_{n-1}$, TLM calculates the 5% values which are 1.16375, 0.1833 and 0.0246 respectively. TLM takes "NO" option into consideration because all variations are less than their 5% values.

The variations in the approved tool life constants are plotted in Figure 8.14. It can be seen that the variations decrease rapidly after the first test and then they are approximately stable. This means that the predictions of TLA become stable after using the fifth approved tool life.

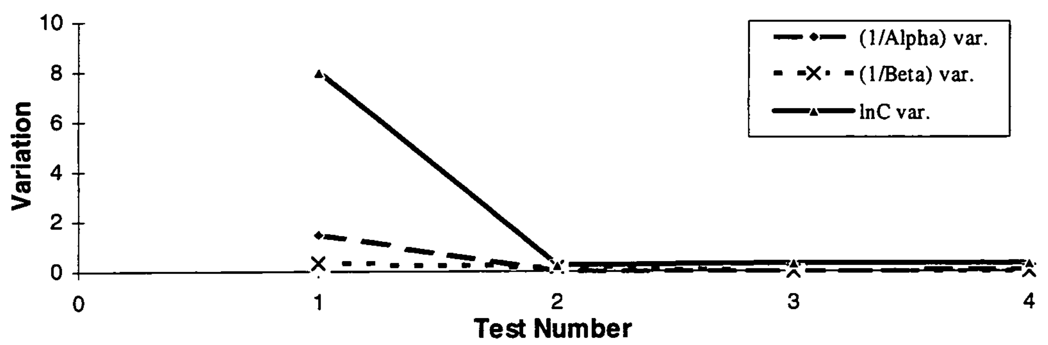

Figure 8.14 Variation in tool life coefficients when finishing EN8 with TP20

- ***The difference between T_{app} and T_{mod}***

TLM retrieves T_{app} and T_{mod} for the last two tests shown in Table 8.2 and calculates the following:

$$\left|T_{mod} - T_{app}\right|_{test4} = |\ 7.31 - 8.58\ | = 1.27$$

$$\left|T_{mod} - T_{app}\right|_{test5} = |\ 6.15 - 6.47\ | = 0.32$$

The "NO" option will be considered as a result of this check (*0.32 < 1.27*).

- ***T_{app}* and the boundary limits calculated by TLA**

The T_{app} and the T_{mod} values with its 95% confidence limits retrieved by TLM for this set of tests are shown in Table 8.8.

Table 8.8 T_{app} and T_{mod} with its 95 % confidence limits

Test no.	T_{app}	T_{mod}	*± limits*	*In*	*Out*
1	4.90	3.04	± 9.264	×	
2	10.05	10.87	± 1.606	×	
3	13.07	13.13	± 0.975	×	
4	8.58	7.31	± 0.737		×
5	6.47	6.15	± 0.634	×	

TLM calculates how many times the approved tool life values lie within the boundary limits calculated by TLA as shown in Figure 8.6 and Table 8.8. TLM takes "YES" (the approved tool life showed an unacceptable fit with regard to the confidence limits) option because test 4 is outside the boundary limits (20 % outside the limits).

Finally, TLM considers "YES" option for this combination (material, grade and type of cut) because the last check results in "YES". The "YES" option indicates that the approved tool life coefficients are not stable and it is recommended to keep recording additional approved points. It must be noted that in this case the failure is marginal and a wider confidence limit would have resulted in stable coefficients.

8.2.3 TLM results when machining EN8 free cutting steel using TP20 insert grade under semi-roughing conditions

- ***Variations in tool life constants***

Table 8.9 shows the required information retrieved by TLM from the management file to apply this check.

Table 8.9 Management file when semi-roughing EN8 using TP20 insert grade

Material sub-class	*Insert grade*	*No. of points*	*Cut type*	*lnC*	$1/\alpha$	$1/\beta$	*lnC var*	$(1/\alpha)$ *var*	$(1/\beta)$ *var*
free-cutting steel	TP20	7	M R	10.202	2.028	2.956			
free-cutting steel	TP20	8	M R	10.200	2.079	2.962	0.002	0.051	0.006

As in the previous two sets of tests, the 5% values of lnC_{n-1}, $(1/\alpha)_{n-1}$ and $(1/\beta)_{n-1}$ calculated by TLM are 0.51, 0.104 and 0.1478 respectively. This check is successful and TLM registers the "NO" option since all the variations are less than their 5 % values. Figure 8.15 shows the variation in the approved tool life coefficients for these tests.

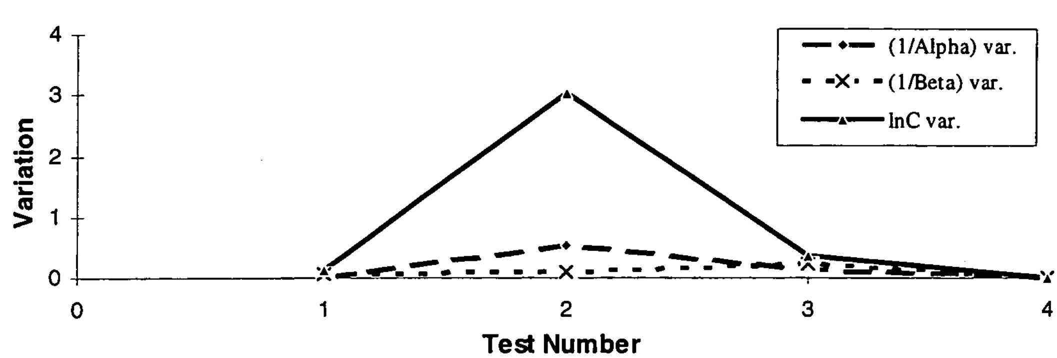

Figure 8.15 Variation in tool life coefficients when semi-roughing EN8 with TP20

Figure 8.15 shows that the coefficients become stable after the second test and their variation is negligible in subsequent tests. This means that different modified values would have been calculated for the first two tests shown in Figure 8.8.

- ***The difference between T_{app} and T_{mod}***

TLM calculates the difference between the approved tool life values and the modified tool life values for the last two tests shown in Table 8.3.

$$\left|T_{mod} - T_{app}\right|_{test4} = 0.05$$

$$\left|T_{mod} - T_{app}\right|_{test5} = 0.69$$

In this case, TLM registers a "YES" option because the difference is getting bigger.

- ***T_{app} and the boundary limits calculated by TLA***

For semi-roughing EN8 steel using TP20 insert grade, TLM retrieves the values shown in Table 8.10 from the operations database.

Table 8.10 T_{app} and T_{mod} with its 95 % confidence limits

Test no.	T_{app}	T_{mod}	*± limits*	*In*	*Out*
1	19.45	18.26	± 10.241	×	
2	7.80	13.93	± 2.021		×
3	11.17	9.48	± 1.558		×
4	9.13	9.18	± 1.193	×	
5	11.60	11.36	± 1.115	×	

Again here TLM registers a "YES" result since 40 % of the approved values lie outside the boundary limits calculated by TLA as shown in Figure 8.9 and Table 8.10.

Finally, this assessment results in the conclusion that the approved coefficients are not stable since checks 2 and 3 failed. The system will keep recording additional approved points to improve future predictions.

8.2.4 TLM results when machining difficult stainless steel (316) using TP35 insert grade under semi-roughing conditions

- ***Variations in tool life constants***

Table 8.11 shows the last two approved records retrieved by TLM when cutting difficult stainless steel (316) using TP35 insert grade under semi-roughing machining conditions.

Table 8.11 Management file when semi-roughing SS316 using TP35 insert grade

Material sub-class	*Insert grade*	*No. of points*	*Cut type*	*lnC*	*1/α*	*1/β*	*lnC var*	*(1/α) var*	*(1/β) var*
Difficult stainless steel	TP35	6	MR	15.370	3.557	3.478			
Difficult stainless steel	TP35	7	MR	15.289	3.548	3.505	0.081	0.009	0.027

For the lnC_{n-1}, $(1/\alpha)_{n-1}$ and $(1/\beta)_{n-1}$, TLM calculates the 5% values which are 0.7685, 0.17785 and 0.1739 respectively.

TLM considers the "NO" option since all the variations are less than the 5% value of the $(n-1)$ values.

Figure 8.16 shows the variations in the approved tool life constants for these tests. It is quite obvious that the variations in the three constants stabilised after only five approved points (4 from the initial testing and one from the current set of tests). This means that the predictions from TLA are very close to the approved values and only the modified tool life value for test 1 should be more accurate when re-calculated using the stable, approved coefficients.

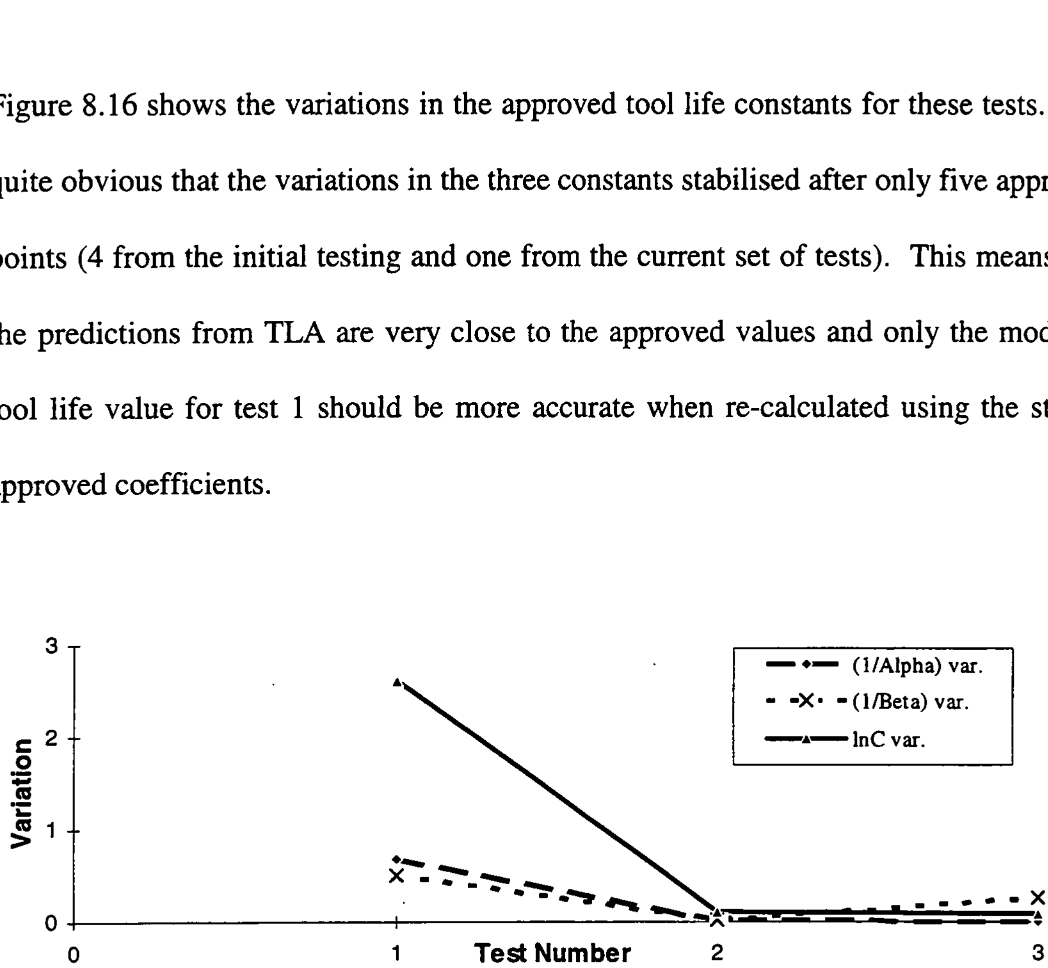

Figure 8.16 Variation in tool life coefficients when semi-roughing SS316 with TP35

- ***The difference between T_{app} and T_{mod}***

From Table 8.4, TLM calculates the following:

$$\left|T_{mod} - T_{app}\right|_{test4} = 0.37$$

$$\left|T_{mod} - T_{app}\right|_{test5} = 0.10$$

TLM registers the "NO" option, because the difference is getting smaller (i.e., *0.10 < 0.37*).

- ***T_{app} and the boundary limits calculated by TLA***

The retrieved information for this check is shown in Table 8.12.

Table 8.12 T_{app} and T_{mod} with its 95 % confidence limits

Test no.	T_{app}	T_{mod}	*± limits*	*In*	*Out*
1	6.30	8.09	± 2.005	×	
2	23.72	23.43	± 0.676	×	
3	8.45	8.82	± 0.493	×	
4	8.32	8.22	± 0.354	×	

Again, TLM registers the "NO" option because all the approved values lie within the boundary limits calculated by TLA as shown in Figure 8.12 and Table 8.12.

Because all the three checks resulted in "NO", TLM considers that "no" noticeable variation in the approved tool life coefficients was found and advise the user to stop recording any additional approved points for the current combination of material sub-class, grade and type of operation.

8.3 DISCUSSION

A series of flank wear curves were created for three grades of indexable inserts namely, TP10, TP20 and TP35 when cutting free-cutting steel (EN8) and difficult stainless steel (316) under different machining conditions. All curves exhibit a similar primary wear region followed by a linear secondary wear region and terminated by the initial stage of tertiary wear. In the primary wear region, a small wear land develops quickly, having a width of 0.05 mm, at all cutting velocities and for all workpiece materials tested. The secondary linear wear stage continued up to a flank wear land width which varied in the different tests. The tertiary wear stage was more pronounced at higher cutting velocities (see the first and second sets of tests) than when lower cutting velocities were used (see the last set of tests).

These tests were aimed at the assessment of functionality of the TLA and TLM modules. The basic assumption behind developing TLA was that tool life prediction from an initial, theoretical set of data is inaccurate. For this reason a closed loop system was created by applying dynamic multiple regression to real, approved tool life values obtained through experimentation. The results prove that TLA modifications of tool life are much closer to real values than the initial tool life predictions. Within an industrial environment, one may use a consistent criterion for determining tool life such as type of chip produced, power consumption or increased noise levels and process instability. Using these criteria, the approved tool life can be calculated and fed back into the system's database.

The basic hypothesis of TLM was that the approved tool life coefficients for a given material, grade and operation, become stable after collecting a certain number of approved points. The results of the testing phase prove that this is the case but this consolidation requires a different number of approved points for various materials and grades. TLM will allow a company to stop recording approved tool life values after achieving stable coefficients.

Chapter 9

TOOL LIFE BALANCING AND REQUIREMENT PLANNING

9.1 DEFINITIONS AND DERIVATION OF THE OBJECTIVE FUNCTION

Recently, the need for a method to optimally manage tool replacement has grown due to the continuous development in computer aided automation and increased customer concern over large batch sizes and quality. The benefits that can be achieved from optimal tool replacement include optimized machining to set up time distribution for extended production periods, reduced machine downtime and lower production cost. The objective function is usually unit cost minimization or production rate maximization. Levi and Rossetto (1978) concluded that tool replacement policies appeared to offer large margins for improvement of machining economics. La Commare et al. (1983) stated that it is essential in production to find tool replacement policies that can be used to minimize the machine cost per workpiece and proposed a simulation technique for determining optimal cutting conditions with different tool replacement strategies. However, it is well recognized that a more exact analysis of the machining economics problem can be obtained if the stochastic nature of tool life is taken into account [Wager and Barash 1971; Sekhon 1983]. Simulation based solutions to the machining economics problem with stochastic tool lives were presented by many authors [Fenton and Joseph 1979; Koulamas et al. 1987]. Sheikh et al. (1980) attempted to determine analytically the optimal cutting conditions and tool replacement policies in a machining system and the resulting equations were solved by numerical methods. However, the optimal cutting velocity and feed rate were determined sequentially instead of being determined simultaneously. One of the variables (velocity or feed) had to be selected and then the optimal value of the other variable was determined. Another limitation of Sheikh's approach is that it is applicable only to unconstrained machining process, while the real processes are constrained by allowable feed, machine power or surface finish requirements.

This Chapter addresses the problem of controlling and balancing the wear rate of the cutting edge. Tool wear balancing refers to the modification of wear rate of a tool's cutting edge by the appropriate alteration of cutting conditions (cutting velocity and feed rate) [Maropoulos 1989].

Cutting velocity and feed rate affect tool life and the number of components to be machined per cutting edge. Assume that the cutting velocity and feed rate used in one operation, resulted in changing an edge after 68 components and the production batch size is 70 parts. Tool set up flexibility should be improved by reducing the cutting velocity (or feed rate) slightly to increase tool life to finish the required batch. By using this method it is also possible to balance the wear rates of several tools (cutting edges) so that each one will machine the number of parts that optimize the overall tool changing strategy. The importance of this module lies in the fact that the tool replacement policy is optimized by an appropriate change in cutting data so that the production of a number of batches will be optimized. In order to develop such methods the cost function to be minimized is defined in terms of the cost per operation (C_o).

$$C_o = t_{2,o}\, x + x\, t_{2,o} \frac{t_3}{T} + t_{2,o} \frac{y}{T} \tag{9.1}$$

where; $t_{2,o}$ is the cutting time (min), x is the cost rate of the machine (£/min), t_3 is the tool changing time (min), T is the life of the cutting edge (min) and y is the tool cost per cutting edge (£).

The cost per part (C_p), processed using m operations can be calculated as follows:

$$\begin{aligned} C_p &= x\, t_1 + (t_{2,1}\, x + x\, t_3 \frac{t_{2,1}}{T_1} + y \frac{t_{2,1}}{T_1}) \\ &+ (t_{2,2}\, x + x\, t_3 \frac{t_{2,2}}{T_2} + y \frac{t_{2,2}}{T_2}) \\ &\vdots \\ &+ (t_{2,m}\, x + x\, t_3 \frac{t_{2,m}}{T_m} + y \frac{t_{2,m}}{T_m}) \end{aligned} \tag{9.2}$$

where; t_1 is the component set up time (min).

Equation 9.2 can be written as follows:

$$C_p = x\, t_1 + x \sum_{i=1}^{m} t_{2,i} + x\, t_3 \sum_{i=1}^{m} \left(\frac{t_{2,i}}{T_i}\right) + y \sum_{i=1}^{m} \left(\frac{t_{2,i}}{T_i}\right) \tag{9.3}$$

For any given cutting data, the number of parts the edge can machine (rnc) and the wear rate, are given by [Maropoulos 1989]:

$$rnc = \frac{100}{wear}$$

$$wear = 100\ \frac{t_{2,i}}{T_i}$$

$$t_{2,i} = \frac{\pi\ D\ l}{1000\ \ v\ s} \tag{9.4}$$

where; D is the workpiece diameter (mm), l is the length of the workpiece (m), v is the cutting velocity (m/min) and s is the feed rate (mm/rev).

$$rmc_i = int\left(\frac{T_i}{t_{2,i}}\right) \tag{9.5}$$

By taking the integer, *rmc* is rounded down to the nearest integer number.

When w batches of size q are required, the number of machine stoppages for tool changing (N_{si}) and the number of edges needed (N_{ei}) for tool i can be calculated as follows:

$$N_{si} = int\left(\frac{w\ q}{rmc_i}\right) \tag{9.6}$$

$$N_{ei} = int\left(\frac{w\ q}{rmc_i} + 0.99\right) \tag{9.7}$$

By adding 0.99 and taking the integer, N_{ei} is rounded to the next higher integer number.

Substituting equation 9.5 into 9.3, the total cost per batch (C_b) for producing w batches of size q can be calculated as follows:

$$C_b = w\ q\ x\ t_1 + w\ q\ x\ \sum_{i=1}^{m} t_{2,i} + x\ t_3\ \sum_{i=1}^{m} int\left(\frac{w\ q}{rmc_i}\right) + y\ \sum_{i=1}^{m}\left(\frac{w\ q}{rmc_i} + 0.99\right) \tag{9.8}$$

Substituting equations 9.6 and 9.7 into equation 9.8

$$C_b = w\,q\,x\,t_1 + w\,q\,x \sum_{i=1}^{m} t_{2,i} + x\,t_3 \sum_{i=1}^{m} N_{si} + y \sum_{i=1}^{m} N_{ei} \tag{9.9}$$

The total tool changing time (t_3) can be defined as follows:

$$t_3 = t_s + t_e \tag{9.10}$$

where; t_s (min) is the time to stop the machine, open the right-hand sliding guard, close the guard and start the machine and t_e is the actual insert changing time (min). t_e is always needed no matter how many inserts are changed. However, if more than one insert can be changed in one stop, only one stopping time (t_s) will occur.

The total cost per batch given in equation 9.9 can be expressed as follows:

$$C_b = K_S + K_M + K_T + K_W \tag{9.11}$$

where; K_S is the work set up cost, K_M is the machining cost, K_T is the tool changing cost and K_W is the tool wear cost.

$$K_S = w\,q\,x\,t_1 \tag{9.12}$$

$$K_M = w\,q\,x \sum_{i=1}^{m} t_{2,i} \tag{9.13}$$

$$K_T = x\,t_3 \sum_{i=1}^{m} N_{si}$$

Using the definition given in equation 9.10.

$$K_T = x\left(t_s + t_e\right) \sum_{i=1}^{m} N_{si} \tag{9.14}$$

When more than one edges are replaced at one stop, then there is only one (t_s) time penalty and the insert changing time will occur sequentially. Therefore, equation 9.14 can be modified as follows:

$$K_T = x\, t_s\, N_S + x\, t_e \sum_{i=i}^{m} N_{si} \tag{9.15}$$

where; N_S is the total number of machine stops and is given by:

$$N_S = \sum_{i=1}^{m} N_{si} - N_{mc} \tag{9.16}$$

where; N_{mc} is the number of multiple coincidental stoppages.

$$K_W = \sum_{i=1}^{m} y_i\, N_{ei} \tag{9.17}$$

where; N_{ei} is the number of edges required.

The aim of the current module is to minimize the tool changing cost (K_T) and the tool wear cost (K_W) by reducing the number of machine stops (N_S) and the total number of cutting edges ($N_e = \sum_{i=1}^{m} N_{ei}$) used to machine the required batch of component(s). The following assumptions were made:

- The tool selection for each operation is performed at TPO and does not change.
- Each product is processed using one machine tool (i.e. one machine problem).
- Each machine has multiple tooling capacity.

- The number of machine turret positions is sufficient to accommodate the total number of tools required for machining a component.
- Batches can be machined at any order during the day.

9.2 TRP FUNCTIONALITY

Figure 9.1 shows the overall structure of the tool requirement planning (TRP) module. TRP retrieves the weekly production schedule (Table 9.1) from the production scheduling database. From the weekly production schedule, the user is required to select one machine which may be used to produce several components. The user is also required to select one component which can be produced by the selected machine. For the selected machine and component, the system will retrieve a number of operations for processing the selected part from the operations database.

For the operations required to process a selected component, the tool requirement planning module retrieves the following data from the system's database:

1. Cutting conditions (v , s) and the tool life value (T).
2. The component length and diameter (l and D).
3. Tool life coefficients (lnC, $1/\alpha$, $1/\beta$).
4. Machine data.
5. Tool holder and insert costs.

Having retrieved the above information, TRP applies the retrieved machining conditions (v, s) to calculate the required number of edges (N_e), the number of machine stops (N_S)

for edge changing and the total cost for processing the whole batch of the required component.

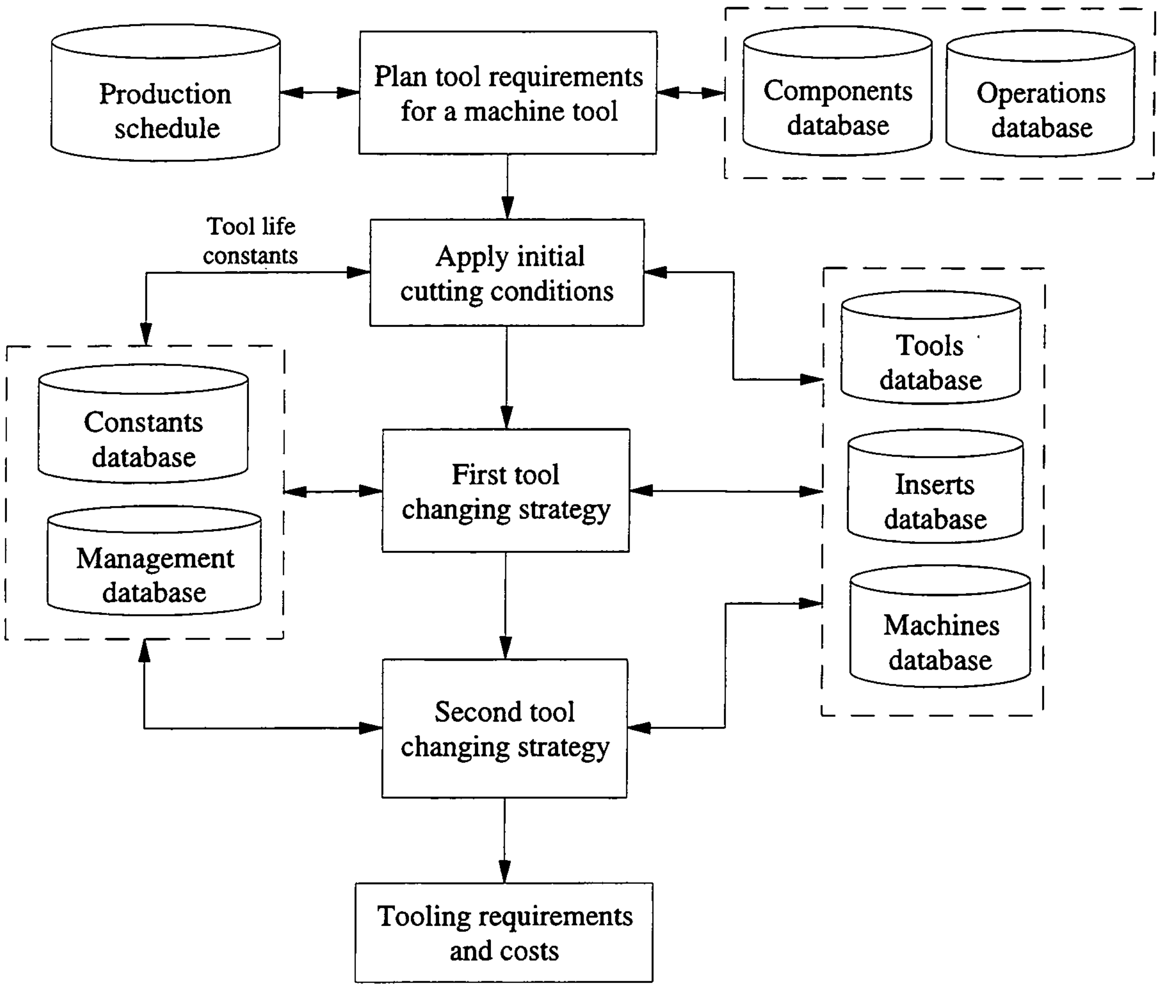

Figure 9.1 The overall structure of TRP

Table 9.1 Weekly production schedule

Plan	*Mach. Code*	*Comp. code*	*Material sub-class*	*No. of operations*	*Batch size*	*No. batches*
Day 1	*CNC-1000*	*A*	*EN8*	*5*	*100*	6
		B	*SS316*	*4*	*100*	5
		C	*EN8*	*3*	*250*	2
Day 2	*Machine X*	:	:	:	:	
Day 3	*Machine Y*	:	:	:	:	

9.3 THE APPLICATION OF THE INITIAL MACHINING CONDITIONS

This section describes the considerations involved during the calculation of tool changes required when applying the initial cutting data. To demonstrate the operation of TRP, it is assumed that the machine tool *CNC-1000* has been selected from Table 9.1 and the planning of tooling requirements relates to component *A*. It must be noted that the same procedure can be used for planning the machining of any set of components such as *A*, *B* and *C*.

The requirement is to produce 600 components of this type in 6 batches of 100 parts each. The process plan for part *A* includes five operations and five tools as shown in Table 9.2. The economic cutting velocity and the tool life value for each operation were calculated separately using the first three modules of the system (TPO, TLP and TLA). For the five operations required to process component *A*, TRP retrieves the data shown in Table 9.2 from the system's database. There are four medium roughing cuts and one finishing operation with predicted tool life values ranging from 5.2 to 14.63 min.

Table 9.2 The operations required to generate component *A*

Operation no.	*Grade*	*Type of cut*	*v*	*s*	T_{sugg}	T_{mod}	*l*	*D*
1	TP20	M R	365	0.22	16.42	11.39	50.0	86.2
2	TP20	M R	350	0.25	14.25	8.53	50.0	78.0
3	TP20	M R	285	0.34	16.27	5.20	50.0	60.4
4	TP20	M R	300	0.24	31.85	12.93	50.0	48.4
5	TP10	F	400	0.13	17.00	14.63	50.0	46.0

For each operation shown in Table 9.2, TRP calculates the machining time, the number of parts per cutting edge *(rnc)*, and the number of edges (N_e) needed to machine the required batches using equations 9.4, 9.5 and 9.7 respectively.

Operation 1

$$t_{2,1} = \frac{\pi\, D\, l}{1000\, v\, s} = \frac{3.14 \times 86.2 \times 50}{1000 \times 365 \times 0.22} = 0.16854 \text{ min}$$

$$rnc_1 = int\left(\frac{T_{mod}}{t_{2,1}}\right) = int\left(\frac{11.39}{0.16854}\right) = 67 \text{ parts}$$

$$N_{e1} = int\left(\frac{w\ q}{rnc_1} + 0.99\right) = int\left(\frac{600}{67} + 0.99\right) = 9 \text{ edges}$$

Operation 2

$$t_{2,2} = \frac{3.14 \times 78 \times 50}{1000 \times 350 \times 0.25} = 0.13995 \text{ min}$$

$$rnc_2 = int\left(\frac{8.53}{0.13995}\right) = 60 \text{ parts}$$

$N_{e2} = 10$ edges

Operation 3

$$t_{2,3} = \frac{3.14 \times 60.4 \times 50}{1000 \times 285 \times 0.34} = 0.09786 \text{ min}$$

$$rnc_3 = int\left(\frac{5.2}{0.09786}\right) = 53 \text{ parts}$$

N_{e3} = 12 edges

Operation 4

$$t_{2,4} = \frac{3.14 \times 48.4 \times 50}{1000 \times 300 \times 0.24} = 0.10554 \text{ min}$$

$$rnc_4 = int\left(\frac{12.93}{0.10554}\right) = 122 \text{ parts}$$

N_{e4} = 5 edges

Operation 5

$$t_{2,5} = \frac{3.14 \times 46 \times 50}{1000 \times 400 \times 0.13} = 0.13888 \text{ min}$$

$$rnc_5 = int\left(\frac{14.63}{0.13888}\right) = 105 \text{ parts}$$

N_{e4} = 6 edges

Table 9.3 shows the summary of the above calculations.

Table 9.3 Summary of the TRP calculations under the initial conditions

Operation no.	***Edge or tool no.***	***Mach. time (min)***	***Parts per edge (rnc)***	***Edges per batch (N_{ei})***
1	*Edge1*	*0.16854*	*67*	*9*
2	*Edge2*	*0.13995*	*60*	*10*
3	*Edge3*	*0.09786*	*53*	*12*
4	*Edge4*	*0.10554*	*122*	*5*
5	*Edge5*	*0.13888*	*105*	*6*

Having calculated the machining time, parts per cutting edge and the total number of edges, TRP applies the current cutting conditions (v, s and a) retrieved from the operations database and calculates the number of machine stops (N_S) for tool changes for producing the total of 600 parts of component *A* using equation 9.16. In this case the machine will be stopped 36 times for edge changing as shown in Table 9.4 and Figure 9.2.

Table 9.4 Machine stoppages under the initial conditions

Stop no.	*Incremental no. of parts*	*Accumulated no. of parts*	*Edge changed*
0	0	0	*Edge1, Edge2, Edge3, Edge4, Edge5*
1	53	53	*Edge3*
2	7	60	*Edge2*
3	7	67	*Edge1*
4	38	105	*Edge5*
5	1	106	*Edge3*
6	14	120	*Edge2*
7	2	122	*Edge4*
8	12	134	*Edge1*
9	25	159	*Edge3*
10	21	180	*Edge2*
11	21	201	*Edge1*
12	9	210	*Edge5*
13	2	212	*Edge3*
14	28	240	*Edge2*
15	4	244	*Edge4*
16	21	265	*Edge3*
17	3	268	*Edge1*
18	32	300	*Edge2*
19	15	315	*Edge5*
20	3	318	*Edge3*
21	17	335	*Edge1*
22	25	360	*Edge2*
23	6	366	*Edge4*
24	5	371	*Edge3*
25	31	402	*Edge1*
26	18	420	*Edge2, Edge5*
27	4	424	*Edge3*
28	45	469	*Edge1*
29	8	477	*Edge3*
30	3	480	*Edge2*
31	8	488	*Edge4*
32	37	525	*Edge5*
33	5	530	*Edge3*
34	6	536	*Edge1*
35	4	540	*Edge2*
36	43	583	*Edge3*

Figure 9.2 is particularly informative since it reveals that there is a wide spread of edge changing interruptions when producing part *A*. The edge changing time (t_e) occurs 37 times and the machine stoppage time (t_s) occurs 36 times.

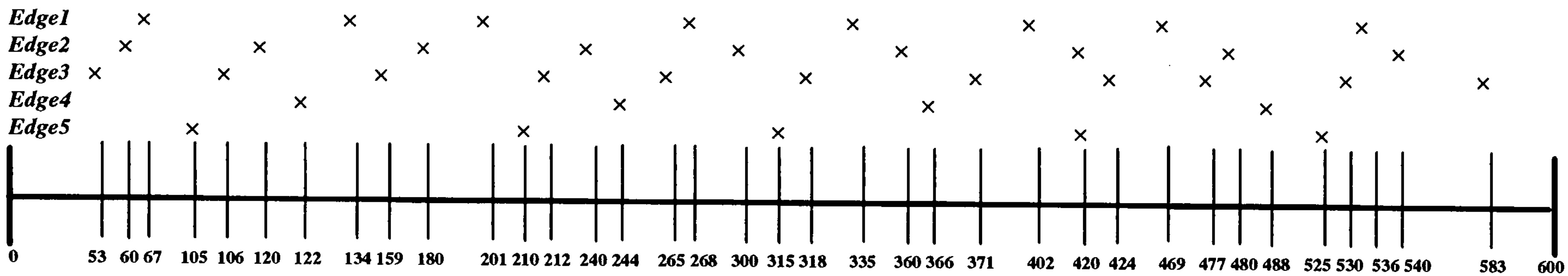

Figure 9.2 Machine stoppages for tool changing and the accumulated number of parts when applying the initial conditions.

Obviously, the effect of such frequent edge changing will be seen when calculating the cost for producing the batches of component *A*. In order to calculate the cost values, TRP retrieves from the system's database the following values:

1. From the machine database, the cost rate of the selected machine (*CNC-1000*), x =1£/min.
2. From the inserts database, the inserts cost (TP10, TP20) = £3.54
3. From the tools database, the tool holder (PCLNR2020-12A) cost = £38.33

The cost per cutting edge is calculated as follows [Maropoulos 1990]:

$$y = \frac{insert\ cost}{0.75 \times number\ of\ cutting\ edges} + \frac{1.3 \times holder\ cost}{400} = £\ 1.3046$$

The above correspond realistically to the tools and machine tool used.

The work set up time (t_1) is dependent upon the size and weight of the workpiece, the type and number of workholding devices and the type of the machine tool. For example, small workpieces can be located in a self-centering chuck of a lathe in less than 0.5 min. Larger workpieces which need a tailstock need longer to set. Finally, very large workpieces machined on vertical boring machines may need several hours to correctly locate and clamp on the machine tool's rotating bed. For the *CNC-1000* lathe, the work set up times were found to be t_1 = 0.3 min for small parts and t_1 = 1.0 min for parts needing tailstock support.

Equally variable can be the edge changing times and machine stoppage times as shown in Table 9.5. For the CNC-1000 lathe it was found that the average times of Table 9.5 were close to what was observed in practice and these were used for the calculation.

Table 9.5 Tool changing time

Rapid or simple tool change	***Average or normal tool change***	***Slow or complex tool change***
$t_s = 0.3$ min	$t_s = 1.0$ min	$t_s = 1.5$ min
$t_e = 0.6$ min	$t_e = 1.5$ min	$t_e = 3.0$ min

Finally, TRP calculates the cost under the initial machining conditions using equations 9.12, 9.13, 9.15 and 9.17 as follows:

Work set up cost $(K_S) = 600 \times 1 \times 0.3 = £180$

Machining cost $(K_M) = 600 \times 1\ [0.16854 + 0.13995 + 0.09786 + 0.10554 + 0.13888] = £390.46$

Tool changing cost $(K_T) = 1\ [36 \times 1.0 + 1.5 \times 37] = £91.5$

Tool wear cost $(K_W) = 1.3046 \times 42 = £54.7932$

The total machining cost per batch $(C_b) = £716.753$

Clearly, the initial tool changing practice suffers from two drawbacks:

- There is frequent tool change which must be communicated to the operator and this may result in errors on the shop floor.
- Time is wasted because the set-up and machine stoppage times for each tool change are counted separately since tool changes are sequential.

The cutting velocity, feed rate and tool life for minimum cost can be modified in order to result in an overall optimum cost for machining [Maropoulos 1989]. This can be achieved by one of the following methods:

- Replace the cutting edge before the end of its life.
- Change the cutting velocity and/or feed rate, thereby increasing tool life and reducing the number of tool changes. In roughing operations, it may be impossible to increase the cutting conditions due to some other constraints such as machine power and it may not be practical to test all the machining constraints at this stage [Maropoulos 1989].

Using this balancing theory [Maropoulos 1989], two new strategies for tool changing optimization have been developed. The logic of the proposal is based on the assumptions that the number of parts between tool changes must be constant and that there must be enough edges to finish the required batch.

9.4 FIRST TOOL CHANGING STRATEGY

9.4.1 Identification of tool with least wear

From the retrieved operations, the cutting edge which can machine the maximum number of parts (rnc_{max}) by applying the present conditions is identified. Then, the ratio of the total production ($w\ q$) to the maximum number of parts per cutting edge (rnc_{max}) is calculated. Obviously, this ratio ($Ratio_{batch}$) corresponds to the minimum number of edges required to complete the batch. This ratio can be calculated for the operation j, assuming it has produced the maximum number of parts as follows:

<u>**Operation j**</u> **($rnc_j = rnc_{max}$)**

$$Ratio_{batch} = int\left(\frac{w\ q}{rnc_{max}} + 0.5\right) \qquad (9.18)$$

Adding 0.5 and taking the integer, the value of $Ratio_{batch}$ is rounded to the nearest integer. The modified number of parts ($rnc_{j,M1}$) for this edge is calculated on this basis:

$$rnc_{j,M1} = int\left(\frac{w\ q}{Ratio_{batch}}\right) \qquad (9.19)$$

The number of edges ($N_{ej,M1}$) required to finish the whole batch considering the modified number of parts can be calculated as follows:

$$N_{ej,M1} = int\left(\frac{w\ q}{rnc_{j,M1}} + 0.99\right) \qquad (9.20)$$

The above value is rounded to the next higher integer number.

When the modified number of parts is greater than the original number of parts using the retrieved conditions ($rnc_{j,M1} > rnc_{max}$), the cutting conditions should be altered in order to machine the new larger number of parts ($rnc_{j,M1}$) either by reducing the cutting velocity or the feed rate. If the modified number of parts is less than the number of parts using the initial conditions ($rnc_{j,M1} < rnc_{max}$), the cutting conditions should not be modified (increased) to avoid violating the machining constraints.

9.4.1.1 Modifying cutting velocity (v)

The modified cutting velocity ($v_{j,M1}$) used to machine the new larger number of parts can be calculated as follows [Maropoulos 1989]:

$$v_{j,M1} = \left(\frac{rnc_{j,M1}\ \pi\ D\ l}{1000\ C\ s^{(1-1/\beta)}} \right)^{\left(\frac{1}{1-1/\alpha} \right)} \qquad (9.21)$$

9.4.1.2 Modifying feed rate (s)

The modified feed rate ($s_{j,M1}$) used to machine the new larger number of parts can be calculated as follows:

$$s_{j,M1} = \left(\frac{rnc_{j,M1}\ \pi\ D\ l}{1000\ C\ v^{(1-1/\alpha)}} \right)^{\left(\frac{1}{1-1/\beta} \right)} \qquad (9.22)$$

9.4.2 Modification of conditions for remaining tools

In order to keep a constant number of parts between edge changes, the modified number of parts which can be machined by the remaining edges will be computed by dividing the new number of parts ($rnc_{j,M1}$) for the edge with the least wear (longest tool life) by the following ratios: 1 : 2 : 3 etc. Another ratio ($Ratio_{rnci,M1}$) is calculated between the modified number of parts ($rnc_{j,M1}$) and the number of parts per edge for the remaining edges required for processing the selected component. This ratio ($Ratio_{rnci,M1}$) can be calculated for operation *i* as follows:

Operation i ***(rnc_i)***

where; $i = 1, 2, 3, \cdots m$, and $i \neq j$ if j is the edge which produces the largest number of parts.

$$Ratio_{rnci,M1} = int\left(\frac{rnc_{j,M1}}{rnc_i} + 0.5\right) \quad (9.23)$$

This ratio is rounded to the nearest integer value.

In a similar manner as described in section 9.4.1, the modified real number of parts and the required number of edges can be calculated using the following equations.

$$rnc_{i,M1} = int\left(\frac{rnc_{j,M1}}{Ratio_{rnci,M1}}\right) \quad (9.24)$$

$rnc_{i,M1}$ is rounded down to the nearest integer number.

$$N_{ei,M1} = int\left(\frac{w\ q}{rnc_{i,M1}} + 0.99\right) \quad (9.25)$$

$N_{ei,M1}$ is rounded to the next higher integer value.

If $rnc_{i,M1} > rnc_i$, there will be an increase in tool life to machine the re-calculated higher number of parts (i.e., reduce v or s). The modified cutting conditions can be calculated using equations 9.21 and 9.22. If $rnc_{i,M1} < rnc_i$, the initial cutting data will be used.

This process is repeated according to the number of operations required to machine the selected component as will be shown in the following example.

9.4.3 An example to demonstrate the first method

In the example discussed in Section 9.3, *edge 4* machines the maximum number of parts (122 parts) as shown in Table 9.3. Therefore, using equation 9.18, $Ratio_{batch}$ is calculated as follows:

Operation 4 ***($rnc_4 = 122$ parts)***

$$Ratio_{batch} = int\left(\frac{600}{122} + 0.5\right) = 5$$

TRP calculates the modified number of parts and the required number of cutting edges using equations 9.19 and 9.20.

$$rnc_{4,M1} = int\left(\frac{600}{5}\right) = 120 \text{ parts}$$

$$N_{e4,M1} = int\left(\frac{600}{120} + 0.99\right) = 5 \text{ edges}$$

No alteration of cutting data is applied ($rnc_4 > rnc_{4,M1}$).

Operation 1 ***($rnc_1 = 67$ parts)***

As discussed in section 9.4.2, the ratio ($Ratio_{rnc1,M1}$) is calculated between the maximum modified number of parts ($rnc_{4,M1}$= 120) and the number of parts (rnc_1) machined by this edge by applying the initial conditions, using equation 9.23.

$$Ratio_{rnc1,M1} = int\left(\frac{120}{67} + 0.5\right) = 2$$

The modified number of parts for this edge can be re-calculated using equation 9.24.

$$rnc_{1,M1} = int\left(\frac{120}{2}\right) = 60 \text{ parts}$$

The number of edges needed in this operation to finish 600 parts of component A can be re-calculated using equation 9.25 as follows:

$$N_{e1,M1} = int\left(\frac{600}{60} + 0.99\right) = 10 \text{ edges}$$

In this operation, the waste of carbide is 7 parts per cutting edge. This is because, the number of parts this edge can machine under the initial machining conditions is reduced by 7 compared with the modified number of parts resulted by applying the first tool changing strategy ($rnc_1 - rnc_{1,M1} = 7$). The cutting conditions (v, s) cannot be modified in this case to avoid violating the machining constraints ($rnc_{1,M1} < rnc_1$).

***<u>Operation 2</u>* (rnc_2 = 60 parts)**

$$Ratio_{rnc2,M1} = int\left(\frac{120}{60} + 0.5\right) = 2$$

$$rnc_{2,M1} = int\left(\frac{120}{2}\right) = 60 \text{ parts}$$

$$N_{e2,M1} = int\left(\frac{600}{60} + 0.99\right) = 10 \text{ edges}$$

In this operation, the same cutting data will be used. This is because $rnc_{2,M1} = rnc_2$.

***<u>Operation 3</u>* (rnc_3 = 53 parts)**

$$Ratio_{rnc3,M1} = int\left(\frac{120}{53} + 0.5\right) = 2$$

$$rnc_{3,M1} = int\left(\frac{120}{2}\right) = 60 \text{ parts}$$

$$N_{e3,M1} = int\left(\frac{600}{60} + 0.99\right) = 10 \text{ edges}$$

TRP retrieves the tool life constants for machining (EN8) free cutting steel using TP20 insert grade under semi-roughing conditions. This is because an alteration (reduction) of cutting data is required in order to machine 60 parts instead of 53 parts. The initial cutting conditions are v = 285 m/min and s = 0.34 mm/rev as shown in Table 9.2.

- *Modifying v*

The modified cutting velocity and the corresponding cutting time can be re-calculated using equations 9.21 and 9.4 respectively.

$$v_{3,M1} = \left(\frac{60 \times 3.14 \times 60.4 \times 50}{1000 \times 26909.913 \times 0.34^{1-2.96237}}\right)^{\left(\frac{1}{1-2.07993}\right)} = 252.48 \text{ m/min}$$

$$t_{2,3} = \frac{3.14 \times 60.4 \times 50}{1000 \times 252.48 \times 0.34} = 0.11047 \text{ min}$$

- *Modifying s*

The modified feed rate and the corresponding machining time cane be re-calculated using equations 9.22 and 9.4 as follows:

$$s_{3.,M1} = \left(\frac{60 \times 3.14 \times 60.4 \times 50}{1000 \times 26909.913 \times 285^{1-2.07993}}\right)^{\left(\frac{1}{1-2.96237}\right)} = 0.318 \text{ mm/rev}$$

$$t_{2,3} = \frac{3.14 \times 60.4 \times 50}{1000 \times 285 \times 0.318} = 0.10463 \text{ min}$$

As expected, the cutting velocity and feed rate are reduced from their original values in order to increase tool life to allow the machining of 60 parts instead of 53 parts.

***<u>Operation 5</u>* (rnc$_5$ = 105 parts)**

$$Ratio_{rnc5,M1} = int\left(\frac{120}{105} + 0.5\right) = 1$$

$$rnc_{5,M1} = int\left(\frac{120}{1}\right) = 120 \text{ parts}$$

$$N_{e5,M1} = int\left(\frac{600}{120} + 0.99\right) = 5 \text{ edges}$$

Again, TRP retrieves the tool life constants for machining free cutting steel (EN8) using TP10 insert grade under finishing conditions. This is because an alteration of cutting data is required in order to machine 120 parts instead of 105 parts. The initial cutting data is v = 400 m/min and s = 0.13 mm/rev as shown in Table 9.2.

- *Modifying v*

The modified cutting velocity and cutting time are re-calculated as follows:

$$v_{5,M1} = \left(\frac{120 \times 3.14 \times 46 \times 50}{1000 \times 4.350624E8 \times 0.13^{1-0.1839}}\right)^{\left(\frac{1}{1-2.93474}\right)} = 373.89 \text{ m/min}$$

$$t_{2,5} = \frac{3.14 \times 46 \times 50}{1000 \times 373.89 \times 0.13} = 0.14858 \text{ min}$$

- *Modifying s*

In the case of modifying s, the modified feed rate and cutting time can be re-calculated as follows:

$$s_{5,M1} = \left(\frac{120 \times 3.14 \times 46 \times 50}{1000 \times 4.350624E8 \times 400^{1-2.93474}}\right)^{\left(\frac{1}{1-0.1839}\right)} = 0.153 \text{ mm/rev}$$

$$t_{2,5} = \frac{3.14 \times 46 \times 50}{1000 \times 400 \times 0.153} = 0.11801 \text{ min}$$

The modified cutting velocity is lower than the original value. However, this is not the case for the feed rate which is increased from 0.13 mm/rev to 0.153 mm/rev in order to machine 120 parts instead of 105 parts. This phenomenon can have very useful applications in machining economics and was first observed by Maropoulos (1989). Its explanation lies in the fact that the exponent of the feed rate in Taylor's equation is less than one for finishing operations. In this particular case $\frac{1}{\beta}$ = 0.1839.

Table 9.6 shows a summary of the above calculations resulting from applying the first tool balancing strategy.

Table 9.6 Summary of TRP calculations by applying the first strategy

Op.	***Parts per edge***		***Edges per batch***		***v***	***s***	***Mod. v***	***Mod. s***
no	***Initial***	***Final***	***Initial***	***Final***	***m/min***	***mm/rev***	***m/min***	***mm/rev***
1	67	60	9	10	365	0.22	No change	No change
2	60	60	10	10	350	0.25	No change	No change
3	53	60	12	10	285	0.34	252.48	0.318
4	122	120	5	5	300	0.24	No change	No change
5	105	120	6	5	400	0.13	373.89	0.153

TRP calculates the number of machine stops by applying this balancing strategy using equation 9.16 as shown in Table 9.7 and Figure 9.3. It is clear that the number of machine stops for edge changing is reduced by 27 when compared with the results by applying the retrieved machining data (36 stops) as discussed in section 9.3 and shown in Table 9.4 and Figure 9.2. More importantly, the wide spread of tool changes shown in Figure 9.2 is replaced by a clustering of changes by producing a constant number of parts. Multiple edge changes are executed in every machine stoppage, thereby reducing the unproductive time due to tool changing.

Table 9.7 Machine stoppages using the first strategy

Stop no.	*Incremental parts*	*Accumulated parts*	*Edge changed*
0	*0*	*0*	*Edge1, Edge2, Edge3, Edge4, Edge5*
1	*60*	*60*	*Edge1, Edge2, Edge3*
2	*60*	*120*	*Edge1, Edge2, Edge3, Edge4, Edge5*
3	*60*	*180*	*Edge1, Edge2, Edge3*
4	*60*	*240*	*Edge1, Edge2, Edge3, Edge4, Edge5*
5	*60*	*300*	*Edge1, Edge2, Edge3*
6	*60*	*360*	*Edge1, Edge2, Edge3, Edge4, Edge5*
7	*60*	*420*	*Edge1, Edge2, Edge3*
8	*60*	*480*	*Edge1, Edge2, Edge3, Edge4, Edge5*
9	*60*	*540*	*Edge1, Edge2, Edge3*

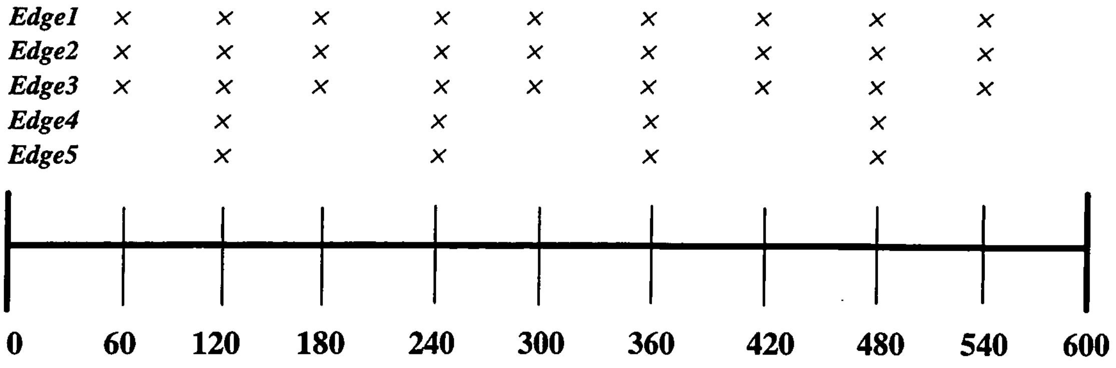

Figure 9.3 Machine stoppages for edge changing and the accumulated number of parts when the first strategy is employed.

TRP calculated the cost per batch when tool life is balanced by altering cutting velocity and feed rate.

- Cost when changing cutting velocity:

$K_S = 600 \times 1 \times 0.3 = £180$

$K_M = 600\ [0.16845 + 0.13995 + 0.11047 + 0.10554 + 0.14858) = £403.79$

$K_T = 1\ [9 \times 1.0 + 1.5 \times 35] = £61.5$

$K_W = 1.3046 \times 40 = £52.184$

$C_b = £697.474$

- Cost when changing feed rate:

$K_S = £180$

$K_M = 600\ [0.16845 + 0.13995 + 0.10463 + 0.10554 + 0.11801) = £381.948$

$K_T = £61.5$

$K_W = £52.184$

$C_b = £675.632$

Table 9.8 shows a summary of the cost calculations when the first method is employed.

Table 9.8 Summary of cost calculations by first method

Cost (£)	Initial	Change *v*	Change *s*
K_s	180.0	180.0	180.0
K_M	390.46	403.79	381.011
K_T	91.50	61.50	61.50
K_W	54.793	52.184	52.184
C_b	716.753	697.474	675.632

As a result of comparing the three costs shown in Table 9.8, TRP will advise the user to modify the feed rates rather than cutting velocities when this strategy is employed to machine 600 parts of component *A* using the *CNC-1000* lathe machine. This is because the balancing method using feed rate has resulted in lower batch cost than the cutting velocity. It is also clear that there is cost reduction when comparing the balanced methods with the initial conditions, mainly due to tool changing cost.

9.5 SECOND TOOL CHANGING STRATEGY

9.5.1 Identification of tool with least wear

The $Ratio_{batch}$ is calculated between the edge which can machine the maximum number of parts and the required batch size by using equation 9.18 as discussed in section 9.4.1.

The modified number of parts ($rnc_{j,M2}$), the required number of cutting edges ($N_{ej,M2}$) and the cutting time ($t_{2,j}$) can be re-calculated for this edge using equations 9.19, 9.20 and 9.4 respectively.

If the modified number of parts is greater than the original number by applying the initial conditions ($rnc_{j,M2} > rnc_j$), the cutting conditions can be modified using equations 9.21 and 9.22. Otherwise, no alteration of cutting data is applied.

9.5.2 Modification of conditions for remaining tools

In order to keep a constant number of parts between edge changes, the number of parts ($rnc_{i,M2}$) which can be machined by the remaining edges are re-calculated by dividing the modified maximum number of parts ($rnc_{j,M2}$) per edge, by the following ratios: 1 : 1.5 : 2 : 2.5 etc. The following ratio is calculated:

$$Ratio_{rnci,M2} = int\left\{\left(\frac{rnc_{j,M2}}{rnc_i}\times 2\right)+0.5\right\} \tag{9.26}$$

By adding 0.5 and taking the integer, this ratio is rounded to the nearest integer number. The modified number of parts ($rnc_{i,M2}$) is calculated using the following equation:

$$rnc_{i,M2} = int\left(\frac{rnc_{j,M2}}{\left(Ratio_{rnci,M2}/2\right)}\right) \tag{9.27}$$

By taking the integer, the number of parts calculated by equation 9.27 is rounded down to the nearest integer number. The modified number of edges ($N_{ei,M2}$) is calculated as follows:

$$N_{ei,M2} = int\left(\frac{w \times q}{rnc_{i,M2}} + 0.99\right) \tag{9.28}$$

The calculated number of edges is rounded to the next integer number.

Again if $rnc_{i,M2} > rnc_i$, the modified machining conditions are calculated using equations 9.21 and 9.22. Otherwise, no alteration of cutting data is applied. This process is repeated for the retrieved number of operations as will be shown in the next example.

9.5.3 An example to demonstrate the second method

For the example discussed in sections 9.3 and 9.4.3, the $Ratio_{batch}$ is calculated for *edge 4* since it produces the maximum number of parts (122 parts) using equation 9.18.

$$Ratio_{batch} = int\left(\frac{600}{122} + 0.5\right) = 5$$

The modified number of parts and the required number of edges are calculated using equations 9.19 and 9.20.

$$rnc_{4,M2} = int\left(\frac{600}{5}\right) = 120 \text{ parts}$$

$$N_{e4,M2} = int\left(\frac{600}{120} + 0.99\right) = 5 \ edges$$

In this operation, no alteration of cutting data is applied. This is because the number of parts per edge is reduced by 2 ($rnc_4 - rnc_{4,M2} = 2$).

Operation 1 ***(rnc_1 = 67 parts)***

Using equation 9.26, the following ratio is calculated:

$$Ratio_{rnc1,M2} = int \left\{ \left(\frac{120}{67} \times 2 \right) + 0.5 \right\} = 4$$

The modified number of parts and the required number of edges can be calculated using equations 9.27 and 9.28 as follows:

$$rnc_{1,M2} = int \left(\frac{120}{4/2} \right) = 60 \text{ parts}$$

$$N_{e1,M2} = int \left(\frac{600}{60} + 0.99 \right) = 10 \text{ edges}$$

The waste of carbide is 7 parts per cutting edge. This is because the number of parts this edge can machine is reduced by 7. Again, no alteration of cutting data is applied ($rnc_1 > rnc_{1,M2}$).

Operation 2 ***(rnc_2 = 60 parts)***

$$Ratio_{rnc2,M2} = int \left\{ \left(\frac{120}{60} \times 2 \right) + 0.5 \right\} = 4$$

$$rnc_{2,M2} = int \left(\frac{120}{4/2} \right) = 60 \text{ parts}$$

$$N_{e2,M2} = int \left(\frac{600}{60} + 0.99 \right) = 10 \text{ edges}$$

For this operation, the same initial cutting data will be used since $rnc_{2,M2} = rnc_2$.

Operation 3 ***($rnc_3 = 53$ parts)***

$$Ratio_{rnc3,M2} = int\left\{\left(\frac{120}{53} \times 2\right) + 0.5\right\} = 5$$

$$rnc_{3,M2} = int\left(\frac{120}{5/2}\right) = 48 \text{ parts}$$

$$N_{e3,M2} = int\left(\frac{600}{48} + 0.99\right) = 13 \text{ edges}$$

The waste of carbide is 5 parts per edge. This is because the number of parts this edge can machine is reduced by 5 ($rnc_3 - rnc_{3,M2} = 5$). Again, no alteration of cutting data is applied ($rnc_3 > rnc_{3,M2}$).

Operation 5 ***($rnc_5 = 105$ parts)***

$$Ratio_{rnc5,M2} = int\left\{\left(\frac{120}{105} \times 2\right) + 0.5\right\} = 2$$

$$rnc_{5,M2} = int\left(\frac{120}{2/2}\right) = 120 \text{ parts}$$

$$N_{e5,M2} = int\left(\frac{600}{120} + 0.99\right) = 5 \text{ edges}$$

An alteration of cutting data is required in order to machine 120 parts instead of 105 parts.

- *Modifying v*

The modified cutting velocity and the corresponding cutting time are re-calculated using equations 9.21 and 9.4.

$$v_{5,M2} = \left(\frac{120 \times 3.14 \times 46 \times 50}{1000 \times 4.350624E8 \times 0.13^{1-0.1839}} \right)^{\left(\frac{1}{1-2.93474}\right)} = 373.89 \text{ m/min}$$

$$t_{2,5} = \frac{3.14 \times 46 \times 50}{1000 \times 373.89 \times 0.13} = 0.14858 \text{ min}$$

- *Modifying s*

In the case of modifying s, the new feed rate and the corresponding cutting time can be re-calculated using equations 9.22 and 9.4.

$$s_{5,M2} = \left(\frac{120 \times 3.14 \times 46 \times 50}{1000 \times 4.350624E8 \times 400^{1-2.93474}} \right)^{\left(\frac{1}{1-0.1839}\right)} = 0.153 \text{ mm/rev}$$

$$t_{2,5} = \frac{3.14 \times 46 \times 50}{1000 \times 400 \times 0.153} = 0.11801 \text{ min}$$

Table 9.9 shows a summary of this calculations when the second tool balancing strategy is employed.

Table 9.9 Summary of TRP calculations by applying the second strategy

Op.	***Parts per edge***		***Edges per batch***		***v***	***s***	***Mod. v***	***Mod. s***
no	***Initial***	***Final***	***Initial***	***Final***	***m/min***	***mm/rev***	***m/min***	***mm/rev***
1	67	60	9	10	365	0.22	No change	No change
2	60	60	10	10	350	0.25	No change	No change
3	53	48	12	13	285	0.34	No change	No change
4	122	120	5	5	300	0.24	No change	No change
5	105	120	6	5	400	0.13	373.89	0.153

As with the first strategy, the tool requirement planning and balancing module (TRP) calculates the number of machine stops as shown in Table 9.10 and Figure 9.4. The second method results in 19 machine stoppages and 38 insert changes.

Table 9.10 Machine stoppages using the second strategy

Stop no.	*Incremental parts*	*Accumulated parts*	*Edge changed*
0	0	0	Edge1, Edge2, Edge3, Edge4, Edge5
1	48	48	Edge3
2	12	60	Edge1, Edge2
3	36	96	Edge3
4	24	120	Edge1,Edge2, Edge4, Edge5
5	24	144	Edge3
6	36	180	Edge1, Edge2
7	12	192	Edge3
8	48	240	Edge1, Edge2, Edge3, Edge4, Edge5
9	48	288	Edge3
10	12	300	Edge1, Edge2
11	36	336	Edge3
12	24	360	Edge1,Edge2, Edge4, Edge5
13	24	384	Edge3
14	36	420	Edge1, Edge2
15	12	432	Edge3
16	48	480	Edge1,Edge2, Edge3, Edge4, Edge5
17	48	528	Edge3
18	12	540	Edge1, Edge2
19	36	576	Edge3

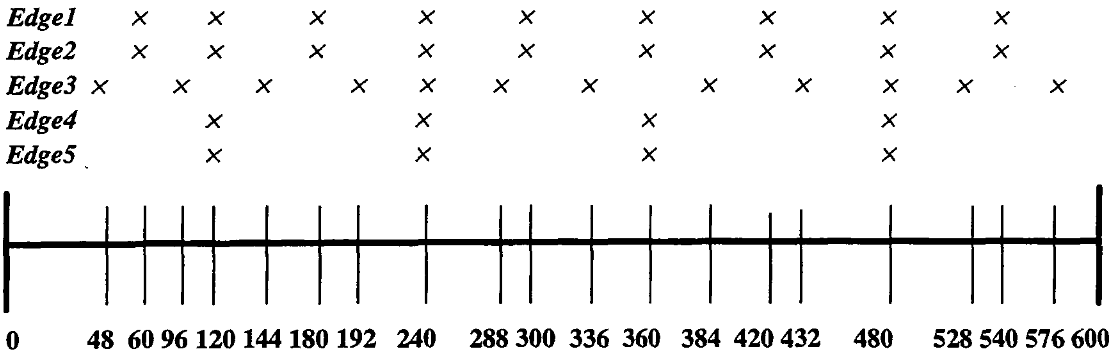

Figure 9.4 Machine stoppages for edge changing and the accumulated number of parts when the second strategy is employed.

TRP calculates the costs as a result of applying the second tool changing policy using equations 9.12, 9.13, 9.15 and 9.17 respectively:

- Cost when changing cutting velocity

$$K_S = 600 \times 1 \times 0.3 = £180$$

$$K_M = 600\ [0.16845 + 0.13995 + 0.09786 + 0.10554 + 0.14858) = £396.228$$

$$K_T = 1\ [19 \times 1.0 + 1.5 \times 38] = £76.0$$

$$K_W = 1.3046 \times 43 = £56.0978$$

$$C_b = £708.326$$

- Cost when changing the feed rate

$$K_S = £180$$

$$K_M = 600\ [0.16845 + 0.13995 + 0.09786 + 0.10554 + 0.11801) = £377.886$$

$$K_T = £76.0$$

$$K_W = £56.0978$$

$$C_b = £689.984$$

Table 9.11 shows a summary of the three cost functions calculated by TRP when the second method is employed.

Table 9.11 Cost calculations by the second strategy

Cost (£)	Initial	Change v	Change s
K_s	180.0	180.0	180.0
K_M	390.46	396.228	377.886
K_T	91.50	76.0	76.0
K_W	54.793	56.098	56.098
C_b	716.753	708.326	689.984

Again, it is clear that there is cost reduction when comparing the balanced methods with the initial conditions.

Table 9.12 shows the results when applying the initial cutting conditions discussed in Section 9.3, as well as the first and second wear balancing strategies discussed in Section 9.4.3 and Section 9.5.3 respectively.

Table 9.12 Summary of the TRP calculations for the three strategies

	Number of edges	*Number of mach. stops*	*Modified parameter*	*Cost per batch (£)*
Initial conditions	42	36	No change	716.753
First strategy	40	9	*Mod. v*	697.474
	40	9	*Mod. s*	675.632
Second strategy	43	19	*Mod. v*	708.326
	43	19	*Mod. s*	689.984

By comparing the results from the three strategies shown in Table 9.12, it is clear that the cost in the first and second strategies are less than the initial case. Furthermore, the two balancing strategies resulted in minimum cost by modifying the feed rates of operations. TRP will advise the user to consider implementing the first tool changing strategy with modified feed rates for machining 600 parts of component *A* using the *CNC-1000* lathe machine.

Apart from the optimization of tool changing, TRP calculates the carbide (or consumable tooling) requirements for the production schedule under consideration. Table 9.12 summarises the cutting edges required for each one of the three methods. If the first strategy is selected there is a total requirement for 40 edges and Table 9.6 shows the exact requirements per operation or tool. In the previous Chapters, the integrated tool life prediction and assessment methods using multiple regression have been shown to address successfully the difficult problem of tool life prediction and control. The application of these methods will allow the accurate planning of tool requirements and this will improve machining efficiency and reduce carbide costs.

9.6 EXAMPLES TO DEMONSTRATE THE TRP OPERATION

9.6.1 Example 1

The requirement is to produce 500 parts of the component *B* shown in Table 9.1. TRP retrieves the four semi-roughing operations required to generate this component as shown in Table 9.13. The predicted tool life ranging from 9.42 to 19.15 min.

Table 9.13 The operations required to generate component *B*

Operation no.	*Grade*	*Type of cut*	*v*	*s*	T_{sugg}	T_{mod}	*l*	*D*
1	TP35	M R	100	0.36	5.29	12.59	50	61.0
2	TP35	M R	105	0.35	4.29	11.69	50	51.0
3	TP35	M R	110	0.29	3.51	19.15	50	39.0
4	TP35	M R	130	0.3	1.71	9.42	50	21.4

For each operation, TRP calculated the machining time, the number of parts per edge and the required number of edges to machine 500 parts of this component. The summary of these calculations are shown in Table 9.14.

Table 9.14 Summary of the TRP calculations under the initial conditions

Operation no.	*Edge or tool no.*	*Mach. time (min)*	*Parts per edge (rnc)*	*Edges per batch* (N_{ei})
1	*Edge1*	*0.26603*	*47*	*11*
2	*Edge2*	*0.21788*	*53*	*10*
3	*Edge3*	*0.19194*	*99*	*6*
4	*Edge4*	*0.08615*	*109*	*5*

Under the present cutting conditions, the edge changing time occurs 28 times and the machine stoppage time occurs 28 times as shown in Table 9.15 and Figure 9.5.

Table 9.15 Machine stoppages under the initial conditions

Stop no.	*Incremental no. of parts*	*Accumulated no. of parts*	*Edge changed*
0	0	0	*Edge1, Edge2, Edge3, Edge4*
1	47	47	*Edge1*
2	6	53	*Edge2*
3	41	94	*Edge1*
4	5	99	*Edge3*
5	7	106	*Edge2*
6	3	109	*Edge4*
7	32	141	*Edge1*
8	18	159	*Edge2*
9	29	188	*Edge1*
10	10	198	*Edge3*
11	14	212	*Edge2*
12	6	218	*Edge4*
13	17	235	*Edge1*
14	30	265	*Edge2*
15	17	282	*Edge1*
16	15	297	*Edge3*
17	21	318	*Edge2*
18	9	327	*Edge4*
19	2	329	*Edge1*
20	42	371	*Edge2*
21	5	376	*Edge1*
22	20	396	*Edge3*
23	27	423	*Edge1*
24	1	424	*Edge2*
25	12	436	*Edge4*
26	34	470	*Edge1*
27	7	477	*Edge2*
28	18	495	*Edge3*

$$y = \frac{3.54}{0.75 \times 4} + \frac{1.3 \times 38.33}{400} = 1.3046$$

$$K_S = 500 \times 1 \times 0.3 = £150$$

$$K_M = 500\ [0.26603 + 0.21788 + 0.19194 + 0.08615] = £381.0$$

$$K_T = 1\ [28 \times 1.0 + 1.5 \times 28] = £70.0$$

$$K_W = 1.3046 \times 32 = £41.747$$

$$C_b = £642.747$$

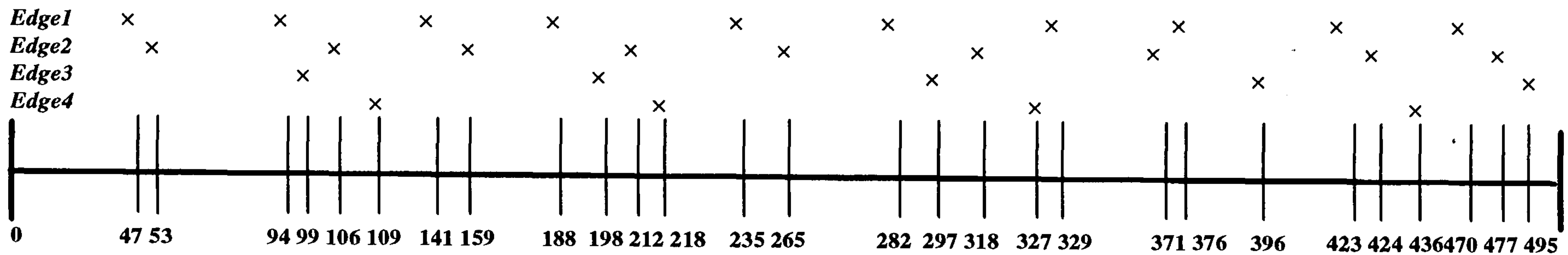

Figure 9.5 Machine stoppages for tool changing and the accumulated number of parts when applying the initial conditions.

9.6.1.1 First tool changing strategy

Table 9.16 shows the modified number of parts, edges per batch and the modified cutting conditions as well as the machining time with the modified velocities and the modified feed rates by applying the first tool wear balancing strategy..

Table 9.16 Summary of TRP calculations when applying the first strategy.

Edge no.	*Mod. Parts per Edge*	*Edges per batch*	*Modify v*	*Mach. time*	*Modify s*	*Mach. time*
Edge 1	*50*	*10*	*97.9*	*0.27186*	*0.352*	*0.27196*
Edge2	*50*	*10*	*No change*	*No change*	*No change*	*No change*
Edge 3	*100*	*5*	*109.9*	*0.19211*	*0.290*	*0.19212*
Edge 4	*100*	*5*	*No change*	*No change*	*No change*	*No change*

The edge changing time occurs 26 times and the machine stoppage time occurs 9 times as shown in Table 9.17 and Figure 9.6.

Table 9.17 Machine stoppages when applying the first strategy

Stop no.	*Incremental no. of parts*	*Accumulated no. of parts*	*Edge changed*
0	0	0	*Edge1, Edge2, Edge3, Edge4*
1	50	50	*Edge1, Edge2*
2	50	100	*Edge1, Edge2, Edge3, Edge4*
3	50	150	*Edge1, Edge2*
4	50	200	*Edge1, Edge2, Edge3, Edge4*
5	50	250	*Edge1, Edge2*
6	50	300	*Edge1, Edge2, Edge3, Edge4*
7	50	350	*Edge1, Edge2*
8	50	400	*Edge1, Edge2, Edge3, Edge4*
9	50	450	*Edge1, Edge2*

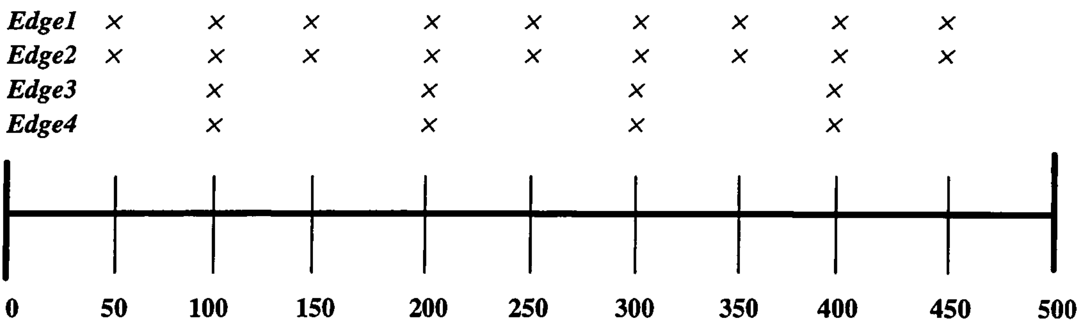

Figure 9.6 Machine stoppages for edge changing and the accumulated number of parts.

a) Cost when modifying v

$K_S = 500 \times 1 \times 0.3 = £150$

$K_M = 500\ [0.27186 + 0.21788 + 0.19211 + 0.08615) = £384.0$

$K_T = 1\ [9 \times 1.0 + 1.5 \times 26] = £48.0$

$K_W = 1.3046 \times 30 = £39.138$

$C_b = £621.138$

b) Cost when modifying s

$K_S = 500 \times 1 \times 0.3 = £150$

$K_M = 500\ [0.27196 + 0.21788 + 0.19212 + 0.08615) = £384.05$

$K_T = 1\ [9 \times 1.0 + 1.5 \times 26] = £48.0$

$K_W = 1.3046 \times 30 = £39.138$

$C_b = £621.188$

9.6.1.2 Second tool changing strategy

Table 9.18 shows the modified number of parts, edges per batch and the modified cutting conditions with the corresponding machining time calculated by the second strategy.

Table 9.18 Summary of TRP calculations when applying the second strategy.

Edge no.	***Mod. Parts per Edge***	***Edges per batch***	***Modify v***	***Mach. time***	***Modify s***	***Mach. time***
Edge 1	*50*	*10*	*97.9*	*0.27186*	*0.352*	*0.27196*
Edge2	*50*	*10*	*No change*	*No change*	*No change*	*No change*
Edge 3	*100*	*5*	*109.9*	*0.19211*	*0.290*	*0.19212*
Edge 4	*100*	*5*	*No change*	*No change*	*No change*	*No change*

The edge changing time occurs 26 times and the machine stoppage time occurs 9 times as shown in Table 9.19 and Figure 9.7.

Table 9.19 Machine stoppages when applying the second strategy

Stop no.	***Incremental no. of parts***	***Accumulated no. of parts***	***Edge changed***
0	0	0	*Edge1, Edge2, Edge3, Edge4*
1	50	50	*Edge1, Edge2*
2	50	100	*Edge1, Edge2, Edge3, Edge4*
3	50	150	*Edge1, Edge2*
4	50	200	*Edge1, Edge2, Edge3, Edge4*
5	50	250	*Edge1, Edge2*
6	50	300	*Edge1, Edge2, Edge3, Edge4*
7	50	350	*Edge1, Edge2*
8	50	400	*Edge1, Edge2, Edge3, Edge4*
9	50	450	*Edge1, Edge2*

Figure 9.7 Machine stoppages for edge changing and the accumulated number of parts.

a) Cost when modifying v

$K_S = 500 \times 1 \times 0.3 = £150$

$K_M = 500\ [0.27186 + 0.21788 + 0.19211 + 0.08615) = £384.0$

$K_T = 1\ [9 \times 1.0 + 1.5 \times 26] = £48.0$

$K_W = 1.3046 \times 30 = £39.138$

$C_b = £621.138$

b) Cost when modifying s

$K_S = 500 \times 1 \times 0.3 = £150$

$K_M = 500\ [0.27196 + 0.21788 + 0.19212 + 0.08615) = £384.05$

$K_T = 1\ [9 \times 1.0 + 1.5 \times 26] = £48.0$

$K_W = 1.3046 \times 30 = £39.138$

$C_b = £621.188$

Finally, the user can select any tool wear balancing strategy to be used to produce 500 parts of component *B* using CNC-1000 machine. This is because both strategies resulted in the same cost as shown in Table 9.20.

Table 9.20 Summary of the TRP calculations for the three strategies

	Number of edges	*Number of mach. stops*	*Modified parameter*	*Cost per batch (£)*
Initial conditions	32	28	No change	642.747
First strategy	30	9	*Mod. v*	621.138
	30	9	*Mod. s*	621.188
Second strategy	30	9	*Mod. v*	621.138
	30	9	*Mod. s*	621.188

9.6.2 Example 2

The requirement is to produce 500 parts of the component *C* shown in Table 9.1. TRP retrieves the operations required to generate this component as shown in Table 9.21. The predicted tool life ranging from 4.52 to 8.45 min.

Table 9.21 The operations required to generate component *C*

Operation no.	*Grade*	*Type of cut*	v	s	T_{sugg}	T_{mod}	l	D
1	TP20	M R	370	0.3	6.90	4.52	90	77.6
2	TP20	M R	320	0.28	15.93	7.30	90	58.4
3	TP20	F	420	0.14	5.98	8.45	90	55.4

For each operation, TRP calculated the machining time, the number of parts per edge and the required number of edges to machine 500 parts of this component. The summary of these calculations are shown in Table 9.22.

Table 9.22 Summary of the TRP calculations under the initial conditions

Operation no.	***Edge or tool no.***	***Mach. time (min)***	***Parts per edge (rnc)***	***Edges per batch (N_{ei})***
1	*Edge1*	*0.19757*	*22*	*23*
2	*Edge2*	*0.18419*	*39*	*13*
3	*Edge3*	*0.26626*	*31*	*17*

Under the present cutting conditions, the edge changing time occurs 50 times and the machine stoppage time occurs 50 times as shown in Table 9.23. Figure 9.8 shows the frequency of machine stoppages for producing 250 parts of component *C*.

$$y = \frac{3.54}{0.75 \times 4} + \frac{1.3 \times 38.33}{400} = 1.3046$$

$$K_S = 500 \times 1 \times 0.3 = £150$$

$$K_M = 500\ [0.19757 + 0.18419 + 0.26626) = £324.01$$

$$K_T = 1\ [50 \times 1.0 + 1.5 \times 50] = £125.0$$

$$K_W = 1.3046 \times 53 = £69.144$$

$$C_b = £668.154$$

Table 9.23 Machine stoppages under the initial conditions

Stop no.	***Incremental no. of parts***	***Accumulated no. of parts***	***Edge changed***
0	0	0	*Edge1, Edge2, Edge3*
1	22	22	*Edge1*
2	9	31	*Edge3*
3	8	39	*Edge2*
4	5	44	*Edge1*
5	18	62	*Edge3*
6	4	66	*Edge1*
7	12	78	*Edge2*
8	10	88	*Edge1*
9	5	93	*Edge3*
10	17	110	*Edge1*
11	7	117	*Edge2*
12	7	124	*Edge3*
13	8	132	*Edge1*
14	22	154	*Edge1*
15	1	155	*Edge3*
16	1	156	*Edge2*
17	20	176	*Edge1*
18	10	186	*Edge3*
19	9	195	*Edge2*
20	3	198	*Edge1*
21	19	217	*Edge3*
22	3	220	*Edge1*
23	14	234	*Edge2*
24	8	242	*Edge1*
25	6	248	*Edge3*
26	16	264	*Edge1*
27	9	273	*Edge2*
28	6	279	*Edge3*
29	7	286	*Edge1*
30	22	308	*Edge1*
31	2	310	*Edge3*
32	2	312	*Edge2*
33	18	330	*Edge1*
34	11	341	*Edge3*
35	10	351	*Edge2*
36	1	352	*Edge1*
37	20	372	*Edge3*
38	2	374	*Edge1*
39	16	390	*Edge2*
40	6	396	*Edge1*
41	7	403	*Edge3*
42	15	418	*Edge1*
43	11	429	*Edge2*
44	5	434	*Edge3*
45	6	440	*Edge1*
46	22	462	*Edge1*
47	3	465	*Edge3*
48	3	468	*Edge2*
49	16	484	*Edge1*
50	12	496	*Edge3*

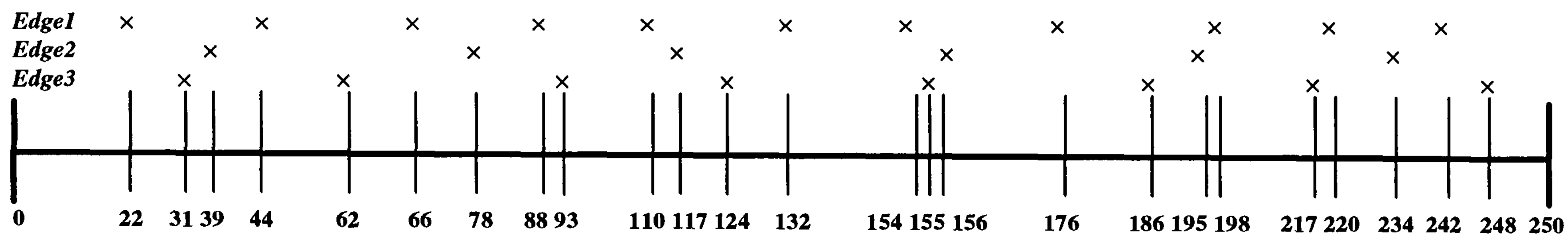

Figure 9.8 Machine stoppages for tool changing and the accumulated number of parts when applying the initial conditions.

9.6.2.1 First tool changing strategy

Table 9.24 shows the modified number of parts, edges per batch and the modified cutting conditions as well as the machining time corresponding to the modified velocity and the modified feed rate by applying the first tool balancing strategy.

Table 9.24 Summary of TRP calculations when applying the first strategy.

Edge no.	*Mod. Parts per Edge*	*Edges per batch*	*Modify v*	*Mach. time*	*Modify s*	*Mach. time*
Edge 1	*19*	*27*	*No change*	*No change*	*No change*	*No change*
Edge2	*38*	*14*	*No change*	*No change*	*No change*	*No change*
Edge 3	*38*	*14*	*390.7*	*0.28620*	*0.204*	*0.18287*

The edge changing time occurs 52 times and the machine stoppage time occurs 26 times as shown in Table 9.25 and Figure 9.9.

a) Cost when modifying v

$$K_S = 500 \times 1 \times 0.3 = £150$$

$$K_M = 500\ [0.19757 + 0.18419 + 0.28620) = £333.98$$

$$K_T = 1\ [26 \times 1.0 + 1.5 \times 52] = £104.0$$

$$K_W = 1.3046 \times 55 = £71.753$$

$$C_b = £659.733$$

b) Cost when modifying s

$$K_S = 500 \times 1 \times 0.3 = £150$$

$K_M = 500\ [0.19757 + 0.18419 + 0.18287) = £282.32$

$K_T = 1\ [26 \times 1.0 + 1.5 \times 52] = £104.0$

$K_W = 1.3046 \times 55 = £71.753$

$C_b = £608.073$

Table 9.25 Machine stoppages when applying the first strategy

Stop no.	***Incremental no. of parts***	***Accumulated no. of parts***	***Edge changed***
0	0	0	*Edge1, Edge2, Edge3*
1	19	19	*Edge1*
2	19	38	*Edge1, Edge2, Edge3*
3	19	57	*Edge1*
4	19	76	*Edge1, Edge2, Edge3*
5	19	95	*Edge1*
6	19	114	*Edge1, Edge2, Edge3*
7	19	133	*Edge1*
8	19	152	*Edge1, Edge2, Edge3*
9	19	171	*Edge1*
10	19	190	*Edge1, Edge2, Edge3*
11	19	209	*Edge1*
12	19	228	*Edge1, Edge2, Edge3*
13	19	247	*Edge1*
14	19	266	*Edge1, Edge2, Edge3*
15	19	285	*Edge1*
16	19	304	*Edge1, Edge2, Edge3*
17	19	323	*Edge1*
18	19	342	*Edge1, Edge2, Edge3*
19	19	361	*Edge1*
20	19	380	*Edge1, Edge2, Edge3*
21	19	399	*Edge1*
22	19	418	*Edge1, Edge2, Edge3*
23	19	437	*Edge1*
24	19	456	*Edge1, Edge2, Edge3*
25	19	475	*Edge1*
26	19	494	*Edge1, Edge2, Edge3*

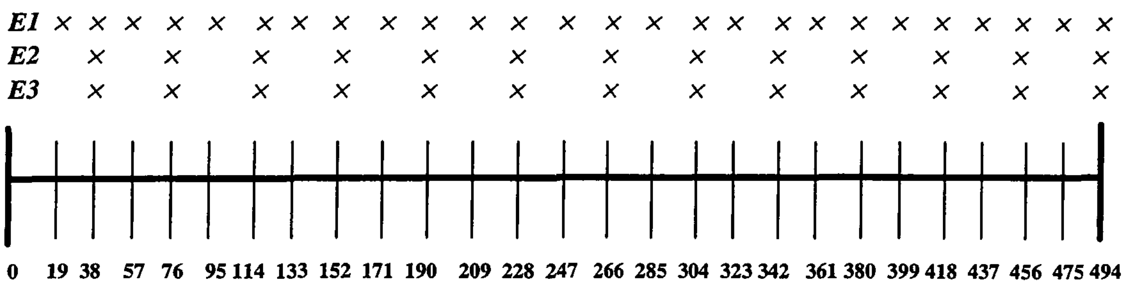

Figure 9.9 Machine stoppages for edge changing and the accumulated number of parts.

9.6.2.2 Second tool changing strategy

Table 9.26 shows the modified number of parts, edges per batch and the modified cutting conditions with the corresponding machining time by applying the second strategy.

Table 9.26 Summary of TRP calculations when applying the second strategy.

Edge no.	***Mod. Parts per Edge***	***Edges per batch***	***Modify v***	***Mach. time***	***Modify s***	***Mach. time***
Edge 1	*25*	*20*	*328.0*	*0.22284*	*0.28*	*0.21110*
Edge2	*38*	*14*	*No change*	*No change*	*No change*	*No change*
Edge 3	*38*	*14*	*390.7*	*0.28620*	*0.2*	*0.18287*

The edge changing time occurs 45 times and the machine stoppage time occurs 26 times as shown in Table 9.27 and Figure 9.10.

Table 9.27 Machine stoppages when applying the second strategy

Stop no.	*Incremental no. of parts*	*Accumulated no. of parts*	*Edge changed*
0	0	0	*Edge1, Edge2, Edge3*
1	25	25	*Edge1*
2	13	38	*Edge2, Edge3*
3	12	50	*Edge1*
4	25	75	*Edge1,Edge2, Edge3*
5	25	100	*Edge1*
6	14	114	*Edge2, Edge3*
7	11	125	*Edge1*
8	25	150	*Edge1, Edge2, Edge3*
9	25	175	*Edge1*
10	15	190	*Edge2, Edge3*
11	10	200	*Edge1*
12	25	225	*Edge1, Edge2, Edge3*
13	25	250	*Edge1*
14	16	266	*Edge2, Edge3*
15	9	275	*Edge1*
16	25	300	*Edge1,Edge2, Edge3*
17	25	325	*Edge1*
18	17	342	*Edge2, Edge3*
19	8	350	*Edge1*
20	25	375	*Edge1,Edge2, Edge3*
21	25	400	*Edge1*
22	18	418	*Edge2, Edge3*
23	7	425	*Edge1*
24	25	450	*Edge1, Edge2, Edge3*
25	25	475	*Edge1*
26	19	494	*Edge2, Edge3*

Figure 9.10 Machine stoppages for edge changing and the accumulated number of parts.

a) *Cost when modifying v*

$K_S = 500 \times 1 \times 0.3 = £150$

$K_M = 500\ [0.22284 + 0.18419 + 0.28620) = £346.62$

$K_T = 1\ [26 \times 1.0 + 1.5 \times 45] = £93.5$

$K_W = 1.3046 \times 48 = £62.621$

$C_b = £652.741$

b) *Cost when modifying s*

$K_S = 500 \times 1 \times 0.3 = £150$

$K_M = 500\ [0.2111 + 0.18419 + 0.18287) = £289.08$

$K_T = 1\ [26 \times 1.0 + 1.5 \times 45] = £93.5$

$K_W = 1.3046 \times 48 = £62.621$

$C_b = £595.201$

Finally, the system will advise the user to employ the second tool wear changing policy with modified feed rate when machining 500 parts of component *C* using CNC-1000 lathe. This is because, this strategy resulted in lower cost as shown in Table 9.28.

Table 9.28 Summary of the TRP calculations for the three strategies

	Number of edges	***Number of mach. stops***	***Modified parameter***	***Cost per batch (£)***
Initial conditions	53	50	No change	668.154
First strategy	55	26	*Mod. v*	659.733
	55	26	*Mod. s*	608.073
Second strategy	48	26	*Mod. v*	652.741
	48	26	*Mod. s*	595.201

Chapter 10

CONCLUSIONS

An off-line tool life control and management system (TLC) has been developed which will form part of an integrated tool selection system (ITS). The operation of the system is based on metal cutting algorithms and statistical techniques such as the multiple regression and least-squares methods. TLC is used to process tool life data from tool catalogues as well as values found by the direct measurement of the wear land on the flank face of carbide inserts for turning operations. TLC consists of five modules namely, the technical planning of the cutting operation (TPO), tool life prediction (TLP), tool life assessor (TLA), tool life management (TLM) and the tool wear balancing and requirement planning (TRP).

The technical planning of the cutting operation module (TPO) was shown to be an efficient, direct and fast method of selecting tools and calculating machining parameters for turning operations by considering the process constraints such as power and rotational speed. The logic applied by TPO to each feature (operation) for selecting tools is based on data found in machining handbooks [MetCut Research Ass., 1980] and has been developed by other researchers [Maropoulos 1990, 1992].

In roughing and semi-roughing cuts, the depth of cut and feed rate are the most influential parameters in making tooling decisions. The selection of tools and the calculation of cutting conditions for finishing operations is constrained by the surface finish requirements. The cutting conditions for all the cutting tests performed herein were calculated using TPO module. The successful operation of this module is demonstrated by the fact that there were no machining constraints active during the tests such as vibration, power limitations and chipping problems.

The tool life prediction methods calculate the tool life values for any selected material sub-class, insert grade and type of cut based on theoretical tool life constants which were derived by applying multiple regression on tool manufacturers' data. Tool manufacturers provide machinists with tables of cutting data for various component material and carbide grade combinations. These cutting conditions result in a "notional" tool life which is usually 15 minutes. Theoretical coefficients calculated using this data are approximate because: (i) Tool manufacturers use general material classes and within each class there may be several material sub-classes which exhibit different machinability characteristics. (ii) The relationship between cutting conditions and tool life is obtained as a result of several field tests which may not use rigorous and consistent tool failure criteria. (iii) Additional tool life points for performing regression are obtained by multiplying this cutting data by certain empirical factors. However, those theoretical coefficients provide a quick starting point in the process of relating cutting conditions to tool life. The calculated process parameters generated by TPO may change during the execution of TLP. This is because TLP predictions are based on the optimization of cutting data using three tool life criteria namely, user defined tool life, tool life for minimum production cost or tool life for maximum production rate.

TLP showed good results in some tool life predictions (using theoretical coefficients) particularly when finishing free cutting steel using TP10 and TP20 insert grades as shown in Table 5.2, Table 5.4 (tests 1, 2 and 4), Table 8.1 (tests 1 and 4) and Table 8.2 (test 1). The reason for this good correlation between prediction and experiment lies in the fact that this specific material is a major material within this particular general class of steels. Consequently, the cutting data given in tool manufacturers' catalogues relate well to it. On the other hand, the inaccuracy of the theoretical coefficients is demonstrated by the relative failure of TLP to accurately predict tool life in the cases shown in Table 5.4 (test 3), Table 5.6, Table 5.8, Table 8.1 (test 2, 3 and 5), Table 8.3 and Table 8.4. This failure is linked to the difficult to machine stainless steel used in these tests. Obviously, this material was not the norm used for constructing the catalogue cutting data tables. The other observation is that tool manufacturers seriously underestimate the tool life of carbides for difficult materials, by providing conservative cutting data and tool life estimations. The reason behind this policy is that cutting data should be successfully applied for the worst material in terms of machinability within a class.

The *Crystal rule induction* system was found to be very efficient and reliable in defining the workpiece material sub-class as a result of giving the material chemical composition. As a result of the tool life experiments, the following observations were made:

- The two most important wear types in metal cutting with carbide tools are flank wear and crater wear.
- Tool flank wear was detected by monitoring the change in power, surface finish, chip size or the noise resulting from the rubbing action of the tool and workpiece.
- The flank wear land is smaller in finishing cuts than in roughing cuts.
- The high cutting velocity performance of carbide inserts is controlled by the wear behaviour of the flank face.
- The use of the cutting fluid reduces tool wear.
- As the cutting velocity increases, the flank wear also increases.
- With an increase in the feed rate, the flank wear also increase but not as fast as with increasing cutting velocity.

The main reason for developing the tool life assessment module (TLA) was in order to improve the operation of the system by creating regression curves based on real tool life values collected from experiments. The assessor system was developed in recognition of the fact that the theoretical tool life coefficients provided variable accuracy of tool life predictions. The concept of a closed loop system is used, whereby the assessor uses real tool life information collected from processes to modify the theoretical predictions. The experimental results obtained in the testing phases proved that the statistical treatment of real tool life values by multiple regression and least-squares methods was successful since the large majority of real tool life values shown in Figures 8.6, 8.9 and 8.12 lie within the tight confidence limits set by the system. Also, in the large majority of tests, the theoretical tool life was successfully modified by TLA and was very close to the experimental value.

Of particular interest is the applicability in the methods for industrial environments. The fact that there is no reliance on any sensorial feedback for collecting real tool life data is expected to enhance the industrial application of the methods. One of the most important aspects in the definition of consistent tool failure criteria. Direct measurement of the wear land is the most accurate method and has been used herein. In industry, the collection of wear information for tools which are replaced can be achieved by using "indirect" criteria of wear such as increased noise, vibration or power consumption. The experimental phase showed that a limited number of observations is required for each material, grade and type of operation combination to create stable tool life coefficients.

The immediate feedback provided by the tool life management (TLM) module is the key indicator for measuring the success of the modified tool life data provided by the tool life assessor. As a result from testing TLM, it was found that at least six approved points (real tool life values) for a given workpiece material, insert grade and type of cut, are required in order to provide the user with stabilized tool life coefficients as discussed in Chapter 8 (Section 8.2). Again, the industrial application of methods is enhanced by the fact that tool life predictions become highly accurate by using such a limited real tool life information.

The tool wear balancing and requirement planning (TRP) module builds on the fact that tool life can be accurately controlled in conjunction with cutting data. Two tool changing methods were developed based on wear balancing theory. The two methods are different in the ratio which controls the calculation of the number of parts each edge can machine (i.e., the constant number of parts between cutting edge changing). As a result of testing TRP with different examples, it was found that the system will always advise the user to balance tool life by modifying the feed rates rather than by modifying cutting velocities. These two strategies resulted in considerable reductions in tool changing costs for producing a given number of components.

The overall system provides a vertical integration of tool life considerations from the initial calculation of tool life based on cutting data, to the subsequent real time modification of tool life predictions using real tool life data and the final adjustment of tool life and cutting data to create an optimal tool replacement strategy.

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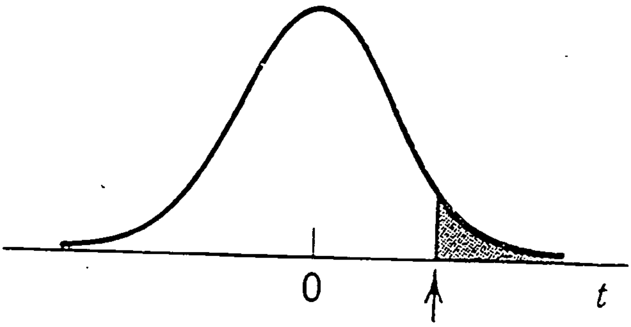
Appendix 1. t distribution critical values

d.o.f	*Tail probability p ($t_{0.025}$)*
1	12.710
2	4.303
3	3.182
4	2.776
5	2.571
6	2.447
7	2.365
8	2.306
9	2.262
10	2.228
11	2.201
12	2.179
13	2.160
14	2.145
15	2.131
16	2.120
17	2.110
18	2.101
19	2.093
20	2.086
21	2.080
22	2.074
23	2.069
24	2.064
25	2.060
26	2.056
27	2.052
28	2.048
29	2.045
30	2.042
40	2.021
50	2.009
60	2.000
80	1.990
100	1.984
120	1.980
1000	1.962
∞	1.960



Critical point. For example: $t_{.025}$ leaves .025 probability in the tail.

Appendix 2. Cutting data for turning, facing and copying (TP10)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Steel Material	1	0.1	490		
		0.2	480		
		0.3	455	430	390
		0.4		380	345
	2	0.1	415		
		0.2	405		
		0.3	385	365	330
		0.4		320	290
	3	0.1	355		
		0.2	345		
		0.3	330	310	280
		0.4		275	245
	4	0.1	295		
		0.2	285		
		0.3	270	255	230
		0.4		225	205
	5	0.1	250		
		0.2	240		
		0.3	230	215	195
		0.4		190	170
	6	0.1	225		
		0.2	220		
		0.3	205	195	
		0.4		175	
	7	0.1	175		
		0.2	170		
		0.3	165	155	
		0.4		135	
Cast Iron	12	0.1	280		
		0.2	290		
		0.3	260	245	220
		0.4		215	195
	13	0.1	225		
		0.2	220		
		0.3	205	195	175
		0.4		175	155
	14	0.1	200		
		0.2	190		
		0.3	180	170	
		0.4		150	

Appendix 2 (cont.). Cutting data for turning, facing and copying (TP15)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	v (m/min)	v (m/min)	v (m/min)
Steel Material	1	0.1	435		
		0.2	420		
		0.3	405	380	345
		0.4		335	305
	2	0.1	370		
		0.2	360		
		0.3	340	320	290
		0.4		285	255
	3	0.1	320		
		0.2	310		
		0.3	295	275	250
		0.4		245	220
	4	0.1	255		
		0.2	250		
		0.3	235	225	200
		0.4		195	180
	5	0.1	220		
		0.2	215		
		0.3	205	190	175
		0.4		170	155
	6	0.1	200		
		0.2	190		
		0.3	180	170	
		0.4		150	
	7	0.1	160		
		0.2	155		
		0.3	145	140	
		0.4		120	
Cast Iron	12	0.1	250		
		0.2	245		
		0.3	235	220	200
		0.4		195	175
	13	0.1	215		
		0.2	210		
		0.3	195	185	170
		0.4		165	150
	14	0.1	175		
		0.2	170		
		0.3	165	155	
		0.4		135	
	15	0.1	140		
		0.2	135		
		0.3	130	120	
		0.4		105	

Appendix 2 (cont.). Cutting data for turning, facing and copying (TP20)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Steel Material	**1**	0.1	405		
		0.2	395		
		0.3	375	355	320
		0.4		315	285
	2	0.1	350		
		0.2	340		
		0.3	325	305	280
		0.4		270	245
	3	0.1	305		
		0.2	295		
		0.3	280	265	240
		0.4		235	210
	4	0.1	250		
		0.2	240		
		0.3	230	215	195
		0.4		190	170
	5	0.1	220		
		0.2	215		
		0.3	205	190	175
		0.4		170	155
	6	0.1	190		
		0.2	180		
		0.3	175	165	150
		0.4		145	130
	7	0.1	155		
		0.2	150		
		0.3	145	135	125
		0.4		120	110
Stainless Steel	**8**	0.1	155		
		0.2	150		
		0.3	145	135	125
		0.4		120	110
	9	0.1	175		
		0.2	170		
		0.3	165	155	
		0.4		135	

Appendix 2 (cont.). Cutting data for turning, facing and copying (TP20)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Cast Iron	**12**	0.1	235		
		0.2	230		
		0.3	215	205	185
		0.4		180	165
	13	0.1	190		
		0.2	185		
		0.3	175	165	150
		0.4		145	130
	14	0.1	165		
		0.2	160		
		0.3	150	140	130
		0.4		125	115
	15	0.1	130		
		0.2	125		
		0.3	120	110	100
		0.4		100	90
	16	0.1	115		
		0.2	115		
		0.3	105	100	90
		0.4		90	80

Appendix 2 (cont.). Cutting data for turning, facing and copying (TP35)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	v (m/min)	v (m/min)	v (m/min)
Steel Material	1	0.1	380		
		0.2	370		
		0.3	350	330	300
		0.4		295	265
	2	0.1	325		
		0.2	315		
		0.3	300	285	255
		0.4		250	225
	3	0.1	265		
		0.2	255		
		0.3	245	230	205
		0.4		200	185
	4	0.1	230		
		0.2	220		
		0.3	210	200	180
		0.4		175	160
	5	0.1	205		
		0.2	200		
		0.3	190	180	165
		0.4		160	145
	6	0.1	150		
		0.2	145		
		0.3	140	130	120
		0.4		115	105
	7	0.1	130		
		0.2	125		
		0.3	120	115	100
		0.4		100	90
Stainless Steel	8	0.1	200		
		0.2	195		
		0.3	185	175	160
		0.4		155	140
	9	0.1	130		
		0.2	125		
		0.3	120	110	100
		0.4		100	90
	10	0.1	95		
		0.2	95		
		0.3	85	80	
		0.4		75	

Appendix 2 (cont.). Cutting data for turning, facing and copying (TP301)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	v (m/min)	v (m/min)	v (m/min)
Stainless Steel	8	0.1	230		
		0.2	220		
		0.3	210	200	180
		0.4		175	160
	9	0.1	155		
		0.2	150		
		0.3	145	135	125
		0.4		120	110
	10	0.1	115		
		0.2	115		
		0.3	105	100	90
		0.4		90	80

Appendix 2 (cont.). Cutting data for turning, facing and copying (TX10)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	v (m/min)	v (m/min)	v (m/min)
Steel Material	6	0.1	200		
		0.2	195		
		0.3	185	175	
		0.4		155	
	7	0.1	160		
		0.2	155		
		0.3	145	140	
		0.4		120	
Cast Iron	12	0.1	250		
		0.2	245		
		0.3	235	220	200
		0.4		195	175
	13	0.1	215		
		0.2	210		
		0.3	200	185	170
		0.4		165	150
	14	0.1	175		
		0.2	170		
		0.3	165	155	
		0.4		135	
	15	0.1	145		
		0.2	140		
		0.3	130	125	
		0.4		110	
	16	0.1	130		
		0.2	125		
		0.3	120	110	
		0.4		100	

Appendix 2 (cont.). Cutting data for turning, facing and copying (TP401)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Stainless Steel	**8**	0.1	210		
		0.2	205		
		0.3	195	185	165
		0.4		160	145
	9	0.1	135		
		0.2	135		
		0.3	125	120	105
		0.4		105	95
	10	0.1	100		
		0.2	100		
		0.3	95	90	80
		0.4		80	70

Appendix 2 (cont.). Cutting data for turning, facing and copying (HX)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Cast Iron	**12**	0.1	180		
		0.2	175		
		0.3	165	155	140
		0.4		140	125
	13	0.1	140		
		0.2	135		
		0.3	125	120	110
		0.4		105	95
	14	0.1	115		
		0.2	115		
		0.3	105	100	90
		0.4		90	80
	15	0.1	95		
		0.2	95		
		0.3	90	85	75
		0.4		75	65
	16	0.1	80		
		0.2	80		
		0.3	75	70	65
		0.4		60	55
Aluminium	**17**	0.1	820		
		0.2	795		
		0.3	765	720	650
		0.4		635	575
	18	0.1	295		
		0.2	285		
		0.3	270	255	230
		0.4		225	205

Appendix 2 (cont.). Cutting data for turning, facing and copying (GC215)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Stainless Steel	**11**	0.1	215		
		0.3		180	

Appendix 2 (cont.). Cutting data for turning, facing and copying (GC235)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Stainless Steel	**11**	0.2	120		
		0.4		105	
		0.6			90

Appendix 2 (cont.). Cutting data for turning, facing and copying (H10A)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Heat Resistant Super Alloys	**19**	0.1	94		
		0.4		43	
		0.8			23
	20	0.1	59		
		0.4		31	
		0.8			15
	21, 24	0.1	42		
		0.4		19	
	22, 25	0.1	34		
	23, 26	0.1	23		
Titanium Alloys	**27**	0.1	195		
		0.4		160	
		0.8			135
	28	0.1	80		
		0.4		65	
		0.8			54
	29	0.1	76		
		0.4		53	
		0.8			45

Appendix 2 (cont.). Cutting data for turning, facing and copying (GC425)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Stainless Steel	**11**	0.2	200		
		0.4		165	
		0.6			120

Appendix 2 (cont.). Cutting data for turning, facing and copying (GC435)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Stainless Steel	**11**	0.2	190		
		0.4		165	
		0.6			100

Appendix 2 (cont.). Cutting data for turning, facing and copying (H10F)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Heat Resistant Super Alloys	**19**	0.3	45		
		0.6		27	
		1.2			12
	20	0.3	30		
		0.6		19	
	21, 24	0.3	17		
	22, 25	0.3	10		
	23, 26	0.3	10		
Titanium Alloys	**27**	0.3	135		
		0.6		112	
		1.2			95
	28	0.3	55		
		0.6		45	
		1.2			36
	29	0.3	48		
		0.6		42	
		1.2			34

Appendix 2 (cont.). Cutting data for turning, facing and copying (H1P)

Material group	Material sub-group	Feed rate	Finishing	Medium Roughing	Roughing
		s (mm/r)	*v (m/min)*	*v (m/min)*	*v (m/min)*
Bronze-Brass Alloys	**30**	0.1	600		
		0.3		430	
		0.5			310
	31	0.1	395		
		0.3		330	
		0.5			275
	32	0.1	285		
		0.3		215	
		0.5			165

Appendix 3. Taylor tool life constants calculated by multiple regression

CUT_TYPE	MATERIAL SUB-CLASS	GRADE	lnC	$1/\alpha$	$1/\beta$	v_{max}	v_{min}
Finishing	Cobalt Base, aged	CC650	30.310	4.840	0.000	320	260
Finishing	Cobalt Base, annealed	CC650	31.060	4.840	0.000	370	310
Finishing	Cobalt Base, cast	CC650	29.430	4.840	0.000	270	200
Finishing	Nickel Base, aged	CC650	31.700	4.840	0.000	420	380
Finishing	Nickel Base, annealed	CC650	32.780	4.840	0.000	520	470
Finishing	Nickel Base, cast	CC650	29.430	4.840	0.000	270	210
Finishing	Cobalt Base, aged	CC670	30.310	4.840	0.000	320	260
Finishing	Cobalt Base, annealed	CC670	31.060	4.840	0.000	370	320
Finishing	Cobalt Base, cast	CC670	29.430	4.840	0.000	270	220
Finishing	Nickel Base, aged	CC670	31.700	4.840	0.000	420	380
Finishing	Nickel Base, annealed	CC670	32.780	4.840	0.000	510	460
Finishing	Nickel Base, cast	CC670	29.430	4.840	0.000	230	190
Finishing	Duplex Stainless	GC215	28.390	4.779	0.000	230	190
M Roughing	Duplex Stainless	GC215	27.637	4.797	0.000	200	160
Finishing	Duplex Stainless	GC235	25.680	4.794	0.000	140	100
M Roughing	Duplex Stainless	GC235	25.080	4.802	0.000	115	90
Roughing	Duplex Stainless	GC235	24.520	4.842	0.000	105	75
Finishing	Duplex Stainless	GC425	28.140	4.796	0.000	220	180
M Roughing	Duplex Stainless	GC425	27.259	4.803	0.000	180	130
Roughing	Duplex Stainless	GC425	25.680	4.794	0.000	140	100
Finishing	Duplex Stainless	GC435	28.015	4.820	0.000	210	170
M Roughing	Duplex Stainless	GC435	27.260	4.803	0.000	180	130
Roughing	Duplex Stainless	GC435	24.814	4.796	0.000	120	80
Finishing	Alpha Grade	H10A	23.850	4.821	0.000	100	50
M Roughing	Alpha Grade	H10A	23.100	4.881	0.000	80	30
Roughing	Alpha Grade	H10A	22.500	4.960	0.000	60	20
Finishing	Alpha-Beta & Beta	H10A	23.770	4.862	0.000	95	40
M Roughing	Alpha-Beta & Beta	H10A	21.990	4.858	0.000	75	25
Roughing	Alpha-Beta & Beta	H10A	21.530	4.940	0.000	60	20
Finishing	Cobalt Base, Aged	H10A	20.273	4.976	0.000	50	25
Finishing	Cobalt Base, Annealed	H10A	21.784	5.009	0.000	60	20
M Roughing	Cobalt Base, Annealed	H10A	15.730	4.395	0.000	30	15
Finishing	Cobalt Base, Cast	H10A	12.940	3.218	0.000	30	15

Appendix 3 (cont.) Taylor tool life constants calculated by multiple regression

CUT_TYPE	MATERIAL SUB-CLASS	GRADE	lnC	$1/\alpha$	$1/\beta$	v_{max}	v_{min}
Finishing	Iron Base, Aged	H10A	22.096	4.754	0.000	80	30
M Roughing	Iron Base, Aged	H10A	18.960	4.725	0.000	50	20
Roughing	Iron Base, Aged	H10A	15.050	4.550	0.000	30	10
Finishing	Iron Base, Annealed	H10A	25.003	4.906	0.000	120	80
M Roughing	Iron Base, Annealed	H10A	20.350	4.692	0.000	60	25
Roughing	Iron Base, Annealed	H10A	16.900	4.520	0.000	30	15
Finishing	Nickel Base, Aged	H10A	20.273	4.976	0.000	50	20
Finishing	Nickel Base, Annealed	H10A	21.784	5.099	0.000	60	20
M Roughing	Nickel Base, Annealed	H10A	15.730	4.395	0.000	30	15
Finishing	Nickel Base, Cast	H10A	12.940	3.218	0.000	30	15
Finishing	Pure Titanium Alloy	H10A	28.080	4.810	0.000	250	170
M Roughing	Pure Titanium Alloy	H10A	27.290	4.840	0.000	180	140
Roughing	Pure Titanium Alloy	H10A	26.333	4.810	0.000	150	110
Finishing	Alpha Grade	H10F	21.752	4.747	0.000	70	30
M Roughing	Alpha Grade	H10F	21.530	4.945	0.000	60	20
Roughing	Alpha Grde	H10F	20.240	4.890	0.000	50	15
Finishing	Alpha-Beta & Beta	H10F	21.106	4.748	0.000	65	25
M Roughing	Alpha-Beta & Beta	H10F	21.780	5.099	0.000	60	20
Roughing	Alpha-Beta & Beta	H10F	20.270	4.980	0.000	50	15
Finishing	Cobalt Base, Aged	H10F	11.584	3.792	0.000	30	10
Finishing	Cobalt Base, Annealed	H10F	17.625	5.257	0.000	35	10
Finishing	Cobalt Base, Cast	H10F	11.584	3.792	0.000	30	10
Finishing	Iron Base, Aged	H10F	20.150	5.130	0.000	50	10
M Roughing	Iron Base, Aged	H10F	15.730	4.400	0.000	30	10
Finishing	Iron Base, Annealed	H10F	21.530	4.940	0.000	65	35
M Roughing	Iron Base, Annealed	H10F	18.370	4.750	0.000	35	15
Roughing	Iron Base, Annealed	H10F	13.440	4.330	0.000	25	10
Finishing	Nickel Base, Aged	H10F	11.584	3.792	0.000	25	10
Finishing	Nickel Base, Annealed	H10F	17.625	5.257	0.000	35	10
Finishing	Nickel Base, Cast	H10F	11.584	3.792	0.000	25	10
Finishing	Pure Titanium Alloy	H10F	26.329	4.815	0.000	150	110
M Roughing	Pure Titanium Alloy	H10F	25.710	4.874	0.000	125	105
Roughing	Pure Titanium Alloy	H10F	24.490	4.780	0.000	115	85

Appendix 3 (cont.) Taylor tool life constants calculated by multiple regression

CUT_TYPE	*MATERIAL SUB-CLASS*	*GRADE*	*lnC*	*1 / α*	*1 / β*	v_{max}	v_{min}
Finishing	Alpha Grade	H13A	22.953	4.797	0.000	85	55
M Roughing	Alpha Grade	H13A	22.500	4.963	0.000	70	35
Roughing	Alpha Grade	H13A	22.120	5.070	0.000	65	30
Finishing	Alpha-Beta & Beta	H13A	22.096	4.754	0.000	80	40
M Roughing	Alpha-Beta & Beta	H13A	21.111	4.748	0.000	70	30
Roughing	Alpha-Beta & Beta	H13A	21.780	5.100	0.000	60	20
Finishing	Aluminium Alloy, cast	H13A	32.380	4.840	0.000	350	250
M Roughing	Aluminium Alloy, cast	H13A	30.060	4.840	0.000	250	150
Roughing	Aluminium Alloy, cast	H13A	27.700	4.840	0.000	150	85
Finishing	Aluminium Alloy, wrought	H13A	38.850	4.840	0.000	550	450
M Roughing	Aluminium Alloy, wrought	H13A	37.330	4.840	0.000	400	320
Roughing	Aluminium Alloy, wrought	H13A	35.060	4.840	0.000	280	210
Finishing	Cobalt Base, Aged	H13A	17.625	5.257	0.000	25	10
Finishing	Cobalt Base, Annealed	H13A	18.368	4.750	0.000	35	10
M Roughing	Cobalt Base, Annealed	H13A	13.800	4.193	0.000	25	10
Finishing	Cobalt Base, Cast	H13A	15.050	4.548	0.000	25	10
Finishing	Copper Alloy	H13A	29.010	4.885	0.000	250	170
M Roughing	Copper Alloy	H13A	27.290	4.842	0.000	180	130
Roughing	Copper Alloy	H13A	25.500	4.800	0.000	130	100
Finishing	Iron Base, Aged	H13A	22.120	5.070	0.000	60	30
M Roughing	Iron Base, Aged	H13A	16.900	4.520	0.000	35	15
Roughing	Iron Base, Aged	H13A	10.170	3.330	0.000	20	10
Finishing	Iron Base, Annealed	H13A	22.230	4.710	0.000	80	45
M Roughing	Iron Base, Annealed	H13A	19.720	4.900	0.000	45	20
Roughing	Iron Base, Annealed	H13A	15.050	4.550	0.000	25	10
Finishing	Lead Alloy	H13A	33.830	4.851	0.000	650	580
M Roughing	Lead Alloy	H13A	32.180	4.860	0.000	450	400
Roughing	Lead Alloy	H13A	30.130	4.820	0.000	315	260
Finishing	Nickel Base, Aged	H13A	17.625	5.257	0.000	25	10
Finishing	Nickel Base, Annealed	H13A	18.368	4.750	0.000	35	15
M Roughing	Nickel Base, Annealed	H13A	13.800	4.193	0.000	20	10
Finishing	Nickel Base, Cast	H13A	15.050	4.548	0.000	25	10
Finishing	Pure Titanium Alloy	H13A	27.310	4.820	0.000	190	140
M Roughing	Pure Titanium Alloy	H13A	26.810	4.900	0.000	155	110
Roughing	Pure Titanium Alloy	H13A	25.970	4.870	0.000	135	100

Appendix 3 (cont.) Taylor tool life constants calculated by multiple regression

CUT_TYPE	MATERIAL SUB-CLASS	GRADE	lnC	$1/\alpha$	$1/\beta$	v_{max}	v_{min}
Finishing	Red Brass and Bronze	H13A	30.619	4.864	0.000	330	290
M Roughing	Red Brass and Bronze	H13A	29.590	4.867	0.000	270	230
Roughing	Red Brass and Bronze	H13A	28.080	4.810	0.000	220	175
Finishing	Aluminium Alloy, cast	H1P	35.240	4.840	0.000	530	480
M Roughing	Aluminium Alloy, cast	H1P	32.250	4.840	0.000	350	300
Roughing	Aluminium Alloy, cast	H1P	31.260	4.840	0.000	250	200
Finishing	Aluminium Alloy, wrought	H1P	40.370	4.840	0.000	830	790
M Roughing	Aluminium Alloy, wrought	H1P	39.370	4.840	0.000	620	580
Roughing	Aluminium Alloy, wrought	H1P	38.260	4.840	0.000	480	440
Finishing	Copper Allloy	H1P	30.149	4.853	0.000	300	260
M Roughing	Copper Alloy	H1P	27.680	4.640	0.000	235	200
Roughing	Copper Alloy	H1P	26.450	4.640	0.000	190	140
Finishing	Lead Alloy	H1P	33.666	4.838	0.000	620	580
M Roughing	Lead Alloy	H1P	32.180	4.860	0.000	450	410
Roughing	Lead Alloy	H1P	30.620	4.860	0.000	330	285
Finishing	Red Brass and Bronze	H1P	31.562	4.824	0.000	415	385
M Roughing	Red Brass and Bronze	H1P	30.930	4.866	0.000	345	310
Roughing	Red Brass and Bronze	H1P	29.820	4.820	0.000	290	255
Finishing	Aluminium Alloy, cast	HX	27.974	4.581	0.355	315	255
M Roughing	Aluminium Alloy, cast	HX	25.052	4.561	2.489	275	155
Roughing	Aluminium Alloy, cast	HX	24.417	4.507	2.394	250	130
Finishing	Aluminium Alloy, wrought	HX	32.977	4.606	0.283	835	750
M Roughing	Aluminium Alloy, wrought	HX	29.724	4.551	2.483	735	495
Roughing	Aluminium Alloy, wrought	HX	29.350	4.557	2.439	650	450
Finishing	High alloy cast iron	HX	22.094	4.619	0.501	90	65
M Roughing	High alloy cast iron	HX	15.940	3.110	0.000	80	45
Roughing	High alloy cast iron	HX	14.730	2.870	0.000	70	35
Finishing	Low alloy cast iron	HX	23.684	4.707	0.797	125	100
M Roughing	Low alloy cast iron	HX	20.703	4.503	2.356	100	70
Roughing	Low alloy cast iron	HX	20.719	4.575	2.172	90	65
Finishing	Low hardness cast iron	HX	25.584	4.548	0.341	180	165
M Roughing	Low hardness cast iron	HX	22.195	4.449	2.565	155	90
Roughing	Low hardness cast iron	HX	21.730	4.462	2.628	140	80

Appendix 3 (cont.) Taylor tool life constants calculated by multiple regression

CUT_TYPE	MATERIAL SUB-CLASS	GRADE	lnC	$1/\alpha$	$1/\beta$	v_{max}	v_{min}
Finishing	Medium hardness cast iron	HX	24.412	4.588	0.440	140	125
M Roughing	Medium hardness cast iron	HX	21.256	4.534	2.688	120	80
Roughing	Medium hardness cast iron	HX	21.266	4.589	2.524	110	75
Finishing	Medium-hard alloy cast iron	HX	23.237	4.680	0.455	105	80
M Roughing	Medium-hard alloy cast iron	HX	18.630	3.593	0.000	100	65
Roughing	Medium-hard alloy cast iron	HX	16.650	3.226	0.000	90	50
Finishing	Difficult tool steel	TP10	26.565	4.550	0.367	235	195
M Roughing	Difficult tool steel	TP10	22.454	3.755	0.000	210	165
Finishing	Free cutting steel	TP10	29.690	4.584	0.298	415	385
M Roughing	Free cutting steel	TP10	23.015	3.446	0.000	365	320
Roughing	Free cutting steel	TP10	22.847	3.478	0.000	330	290
Finishing	Hardened steel	TP10	26.006	4.620	0.251	190	150
M Roughing	Hardened steel	TP10	19.632	3.358	0.000	170	120
Finishing	High carbon steel	TP10	27.974	4.581	0.355	310	260
M Roughing	High carbon steel	TP10	22.243	3.531	0.000	270	210
Roughing	High carbon steel	TP10	22.593	3.665	0.000	245	190
Finishing	Low alloy cast iron	TP10	26.127	4.604	0.432	220	165
M Roughing	Low alloy cast iron	TP10	20.811	3.531	0.000	185	140
Finishing	Low hardness cast iron	TP10	25.639	4.133	0.227	290	245
M Roughing	Low hardness cast iron	TP10	24.508	4.520	2.610	245	165
Roughing	Low hardness cast iron	TP10	24.011	4.496	2.521	220	150
Finishing	Medium hardness cast iron	TP10	26.565	4.550	0.367	235	190
M Roughing	Medium hardness cast iron	TP10	23.494	4.470	2.398	195	135
Roughing	Medium hardness cast iron	TP10	23.309	4.559	2.511	175	120
Finishing	Normal tool steel	TP10	27.475	4.626	0.344	265	215
M Roughing	Normal tool steel	TP10	21.749	3.552	0.000	225	175
Roughing	Normal tool steel	TP10	20.468	3.371	0.000	210	160
Finishing	Structural steel	TP10	29.042	4.594	0.290	370	310
M Roughing	Structural steel	TP10	23.334	3.603	0.000	320	255
Roughing	Structural steel	TP10	21.957	3.420	0.000	280	245
Finishing	Very soft steel	TP10	30.331	4.562	0.292	490	455
M Roughing	Very soft steel	TP10	24.211	3.550	0.000	430	380
Roughing	Very soft steel	TP10	23.943	3.566	0.000	390	345

Appendix 3 (cont.) Taylor tool life constants calculated by multiple regression

CUT_TYPE	MATERIAL SUB-CLASS	GRADE	lnC	1 / α	1 / β	v_{max}	v_{min}
Finishing	Difficult tool steel	TP15	26.127	4.604	0.432	215	170
M Roughing	Difficult tool steel	TP15	20.760	3.520	0.000	185	135
Finishing	Free cutting steel	TP15	29.020	4.572	0.331	385	325
M Roughing	Free cutting steel	TP15	25.861	4.514	2.468	320	220
Roughing	Free cutting steel	TP15	25.755	4.581	2.474	290	200
Finishing	Hardened steel	TP15	24.880	4.532	0.378	170	130
M Roughing	Hardened steel	TP15	18.310	3.160	0.000	150	100
Finishing	High carbon steel	TP15	27.266	4.553	0.312	270	220
M Roughing	High carbon steel	TP15	20.410	3.270	0.000	225	195
Roughing	High carbon steel	TP15	22.680	3.780	0.000	210	160
Finishing	Low alloy cast iron	TP15	26.006	4.620	0.251	190	150
M Roughing	Low alloy cast iron	TP15	19.770	3.390	0.000	170	120
Finishing	Low hardness cast iron	TP15	27.571	4.601	0.246	260	220
M Roughing	Low hardness cast iron	TP15	24.011	4.496	2.521	220	150
Roughing	Low hardness cast iron	TP15	23.827	4.566	2.606	200	135
Finishing	Medium hardness cast iron	TP15	26.019	4.489	0.374	225	180
M Roughing	Medium hardness cast iron	TP15	23.644	4.533	2.325	185	130
Roughing	Medium hardness cast iron	TP15	22.870	4.511	2.565	170	115
Finishing	Medium-hard alloy cast iron	TP15	24.953	4.642	0.307	150	110
M Roughing	Medium-hard alloy cast iron	TP15	19.120	3.430	0.000	130	95
Finishing	Normal tool steel	TP15	26.902	4.600	0.281	230	190
M Roughing	Normal tool steel	TP15	22.170	3.720	0.000	200	150
Roughing	Normal tool steel	TP15	21.070	3.560	0.000	190	140
Finishing	Structural steel	TP15	28.419	4.583	0.327	320	275
M Roughing	Structural steel	TP15	25.246	4.521	2.446	275	190
Roughing	Structural steel	TP15	25.342	4.612	2.383	250	175
Finishing	Very soft steel	TP15	30.142	4.625	0.294	450	390
M Roughing	Very soft steel	TP15	26.656	4.527	2.505	380	260
Roughing	Very soft steel	TP15	26.208	4.530	2.535	345	235
M Roughing	Hardened steel	TP20	20.530	3.642	0.000	145	105
Finishing	Difficult tool steel	TP20	24.064	4.084	0.016	200	155
M Roughing	Difficult tool steel	TP20	20.500	3.490	0.000	175	130
Roughing	Difficult tool steel	TP20	19.280	3.039	0.000	160	110

Appendix 3 (cont.) Taylor tool life constants calculated by multiple regression

CUT_TYPE	*MATERIAL SUB-CLASS*	*GRADE*	*lnC*	*1 / α*	*1 / β*	v_{max}	v_{min}
Finishing	Free cutting stainless	TP20	23.986	4.237	0.016	170	120
M Roughing	Free cutting stainless	TP20	20.530	3.642	0.000	150	100
Roughing	Free cutting stainless	TP20	19.380	3.456	0.000	135	95
Finishing	Free cutting steel	TP20	29.072	4.612	0.292	365	300
M Roughing	Free cutting steel	TP20	25.600	4.531	2.596	305	175
Roughing	Free cutting steel	TP20	23.987	4.309	2.503	280	160
Finishing	Hardened steel	TP20	23.986	4.237	0.016	170	125
Roughing	Hardened steel	TP20	19.380	3.456	0.000	135	100
Finishing	High alloy cast iron	TP20	23.684	4.707	0.797	130	95
M Roughing	High alloy cast iron	TP20	20.703	4.503	2.356	100	70
Roughing	High alloy cast iron	TP20	19.366	4.371	2.607	90	60
Finishing	High carbon steel	TP20	27.475	4.626	0.344	260	220
M Roughing	High carbon steel	TP20	23.449	4.424	2.623	215	120
Roughing	High carbon steel	TP20	23.397	4.504	2.616	195	110
Finishing	Low alloy cast iron	TP20	24.961	4.517	0.373	175	135
M Roughing	Low alloy cast iron	TP20	21.730	4.462	2.628	140	80
Roughing	Low alloy cast iron	TP20	21.900	4.562	2.578	130	75
Finishing	Low hardness cast iron	TP20	26.707	4.530	0.344	245	200
M Roughing	Low hardness cast iron	TP20	23.696	4.532	2.688	205	115
Roughing	Low hardness cast iron	TP20	23.110	4.498	2.660	185	105
Finishing	Medium hardness cast iron	TP20	26.118	4.597	0.321	200	155
M Roughing	Medium hardness cast iron	TP20	22.731	4.502	2.539	165	95
Roughing	Medium hardness cast iron	TP20	22.240	4.500	2.570	150	85
Finishing	Medium-hard alloy cast iron	TP20	24.546	4.639	0.328	145	105
M Roughing	Medium-hard alloy cast iron	TP20	20.298	4.328	2.416	110	75
Roughing	Medium-hard alloy cast iron	TP20	20.703	4.503	2.356	100	70
Finishing	Moderately difficult stainless	TP20	24.755	4.285	0.015	190	150
M Roughing	Moderately difficult stainless	TP20	19.770	3.388	0.000	170	120
Finishing	Normal tool steel	TP20	26.902	4.600	0.281	230	190
M Roughing	Normal tool steel	TP20	23.283	4.469	2.475	190	130
Roughing	Normal tool steel	TP20	23.309	4.559	2.511	175	120
Finishing	Structural steel	TP20	28.155	4.581	0.343	315	265
M Roughing	Structural steel	TP20	24.633	4.481	2.654	265	150
Roughing	Structural steel	TP20	24.422	4.529	2.663	240	135

Appendix 3 (cont.) Taylor tool life constants calculated by multiple regression

CUT_TYPE	MATERIAL SUB-CLASS	GRADE	lnC	$1/\alpha$	$1/\beta$	v_{max}	v_{min}
Finishing	Very soft steel	TP20	29.564	4.584	0.302	415	355
M Roughing	Very soft steel	TP20	25.843	4.456	2.628	355	200
Roughing	Very soft steel	TP20	25.331	4.450	2.646	320	180
Finishing	Difficult castings stainless	TP301	22.871	4.385	0.324	140	90
M Roughing	Difficult castings stainless	TP301	20.180	3.807	0.000	130	80
Roughing	Difficult castings stainless	TP301	18.950	3.619	0.000	110	70
Finishing	Free cutting stainless	TP301	26.896	4.602	0.373	245	200
M Roughing	Free cutting stainless	TP301	23.827	4.566	2.606	200	135
Roughing	Free cutting stainless	TP301	23.452	4.534	2.385	180	125
Finishing	Moderately difficult stainless	TP301	25.332	4.606	0.267	170	125
M Roughing	Moderately difficult stainless	TP301	20.530	3.642	0.000	150	105
Roughing	Moderately difficult stainless	TP301	19.380	3.456	0.000	140	100
Finishing	Difficult castings stainless	TP35	14.609	2.548	0.060	120	65
M Roughing	Difficult castings stainless	TP35	21.501	4.307	0.000	100	55
Finishing	Difficult tool steel	TP35	23.833	4.235	0.016	165	125
M Roughing	Difficult tool steel	TP35	21.900	4.562	2.578	130	75
Roughing	Difficult tool steel	TP35	20.843	4.475	2.839	120	65
Finishing	Free cutting stainless	TP35	24.524	4.131	0.015	210	165
M Roughing	Free cutting stainless	TP35	9.993	1.348	0.081	175	120
Roughing	Free cutting stainless	TP35	10.086	1.394	0.082	160	110
Finishing	Free cutting steel	TP35	28.597	4.601	0.327	335	390
M Roughing	Free cutting steel	TP35	25.012	4.495	2.666	285	160
Roughing	Free cutting steel	TP35	24.721	4.525	2.629	255	145
Finishing	Hardened steel	TP35	22.678	4.122	0.021	145	105
M Roughing	Hardened steel	TP35	20.927	4.479	2.595	115	65
Roughing	Hardened steel	TP35	20.555	4.481	2.410	100	60
Finishing	High carbon steel	TP35	26.896	4.602	0.373	245	200
M Roughing	High carbon steel	TP35	23.314	4.495	2.760	200	110
Roughing	High carbon steel	TP35	22.387	4.365	2.164	180	100
Finishing	Moderately difficult stainless	TP35	22.678	4.122	0.021	145	100
M Roughing	Moderately difficult stainless	TP35	20.976	3.900	0.000	130	90
Roughing	Moderately difficult stainless	TP35	20.180	3.810	0.000	120	70

Appendix 3 (cont.) Taylor tool life constants calculated by multiple regression

CUT_TYPE	MATERIAL SUB-CLASS	GRADE	lnC	1 / α	1 / β	v_{max}	v_{min}
Finishing	Normal tool steel	TP35	26.522	4.599	0.302	220	170
M Roughing	Normal tool steel	TP35	22.387	4.365	2.614	180	100
Roughing	Normal tool steel	TP35	22.544	4.482	2.600	165	95
Finishing	Structural steel	TP35	27.693	4.607	0.318	285	225
M Roughing	Structural steel	TP35	24.422	4.578	2.694	230	130
Roughing	Structural steel	TP35	23.588	4.453	2.463	205	120
Finishing	Very soft steel	TP35	29.112	4.565	0.325	390	335
M Roughing	Very soft steel	TP35	25.363	4.434	2.666	330	185
Roughing	Very soft steel	TP35	25.397	4.520	2.654	300	170
Finishing	Difficult castings stainless	TP401	23.195	4.601	0.411	120	80
M Roughing	Difficult castings stainless	TP401	18.950	3.620	0.000	110	70
Roughing	Difficult castings stainless	TP401	17.610	3.410	0.000	100	60
Finishing	Free cutting stainless	TP401	26.499	4.569	0.293	220	180
M Roughing	Free cutting stainless	TP401	23.651	4.604	2.593	185	125
Roughing	Free cutting stainless	TP401	23.197	4.567	2.388	165	115
Finishing	Moderately difficult stainless	TP401	24.781	4.726	0.645	150	115
M Roughing	Moderately difficult stainless	TP401	19.120	3.430	0.000	130	95
Roughing	Moderately difficult stainless	TP401	20.560	3.850	0.000	115	80
Finishing	Difficult tool steel	TX10	26.237	4.568	0.308	210	165
M Roughing	Difficult tool steel	TX10	21.070	3.560	0.000	185	135
Finishing	Hardened steel	TX10	24.880	4.532	0.378	175	125
M Roughing	Hardened steel	TX10	18.310	3.160	0.000	155	105
Finishing	High alloy cast iron	TX10	24.546	4.639	0.328	145	105
M Roughing	High alloy cast iron	TX10	20.980	3.900	0.000	130	85
Finishing	Low alloy cast iron	TX10	26.006	4.620	0.251	190	140
M Roughing	Low alloy cast iron	TX10	19.770	3.390	0.000	175	115
Finishing	Low hardness cast iron	TX10	27.571	4.601	0.246	265	215
M Roughing	Low hardness cast iron	TX10	22.000	3.580	0.000	235	175
Roughing	Low hardness cast iron	TX10	20.920	3.440	0.000	210	155
Finishing	Medium hardness cast iron	TX10	26.635	4.571	0.286	225	185
M Roughing	Medium hardness cast iron	TX10	21.780	3.660	0.000	195	145
Roughing	Medium hardness cast iron	TX10	20.760	3.520	0.000	180	135
Finishing	Medium-hard alloy cast iron	TX10	24.386	4.543	0.428	160	115
M Roughing	Medium-hard alloy cast iron	TX10	19.380	3.460	0.000	140	100

The cutting data recommended for cutting free-cutting steel (e.g., EN8) using the TP20 insert grade are logarithmically transformed and shown in the Table below. These conditions corresponds to medium roughing (depth of cut = 3 mm) and are valid for turning, facing and copying operation.

Cutting conditions for turning EN8 using TP20 grade under semi-roughing conditions

lnT_i	lnv_i	lns_i	$lnT_i - \overline{lnT}$	$lnv_i - \overline{lnv}$	$lns_i - \overline{lns}$
2.708	5.720	−1.204	−0.795	0.434	−0.490
3.401	5.568	−1.204	−0.101	0.282	−0.490
3.807	5.485	−1.204	0.304	0.199	−0.490
4.094	5.421	−1.204	0.592	0.135	−0.490
2.708	5.598	−0.916	−0.795	0.312	−0.202
3.401	5.447	−0.916	−0.101	0.161	−0.202
3.807	5.361	−0.916	0.304	0.075	−0.202
4.094	5.298	−0.916	0.592	0.012	−0.202
2.708	5.347	−0.511	−0.795	0.061	−0.203
3.401	5.198	−0.511	−0.101	−0.088	−0.203
3.807	5.112	−0.511	0.304	−0.174	−0.203
4.094	5.043	−0.511	0.592	−0.243	−0.203
2.708	5.165	−0.223	−0.795	−0.121	−0.491
3.401	5.017	−0.223	−0.101	−0.269	−0.491
3.807	4.927	−0.223	0.304	−0.359	−0.491
4.094	4.868	−0.223	0.592	−0.418	−0.491

From the Table one can calculate the following:

$\overline{lnT} = 3.5026 \qquad \overline{lnv} = 5.286 \qquad \overline{lns} = -0.7136$

$$\sum(\ ln v_i - \overline{lnv}\ ) = 0.0006$$

$$\sum(\ ln s_i - \overline{lns}\ ) = 0.0071$$

$$\sum(\ ln v_i - \overline{lnv}\ )\left(ln T_i - \overline{lnT}\right) = -0.9373$$

$$\sum(\ lns_i - \overline{lns}\ )\left(ln T_i - \overline{lnT}\right) = 0.000$$

$$\sum\left(ln v_i - \overline{lnv}\ \right)^2 = 0.9465$$

$$\sum\left(ln s_i - \overline{lns}\ \right)^2 = 2.2529$$

$$\sum\left[\left(ln v_i - \overline{lnv}\ \right)\left(lns_i - \overline{lns}\ \right)\right] = -1.2908$$

Estimating equations (4.6) and (4.7).

$$-0.9373 = 0.9465\ (-\hat{\frac{1}{\alpha}}\ ) + (-1.2908)\ (-\hat{\frac{1}{\beta}}\ ) \qquad \text{(i)}$$

$$0.0 = (-1.2908)\ (-\hat{\frac{1}{\alpha}}\ ) + 2.2529\ (-\hat{\frac{1}{\beta}}\ ) \qquad \text{(ii)}$$

From equation (ii)

$$\hat{\frac{1}{\alpha}} = 1.745\ (\hat{\frac{1}{\beta}}\ ) \qquad \text{(iii)}$$

substituting into equation (i)

$$-0.9373 = 1.652\ (-\hat{\frac{1}{\beta}}\ ) + (-1.2908)\ (-\hat{\frac{1}{\beta}}\ )$$

$$-\hat{\frac{1}{\beta}} = -2.596$$

Substituting into equation (iii)

$$-\hat{\frac{1}{\alpha}} = -4.53$$

From equation (4.8):

$$ln\hat{C} = 3.5026 - (-4.53) \times 5.286 - (-2.596) \times (-0.7136)$$

$$ln\hat{C} = 25.596$$

Equation (4.2) can be written as:

$$ln\hat{T} = 25.596 - (-4.53)\ ln v - (-2.596)\ ln s$$

Appendix 5. Pictures of some indexable inserts used in the initial testing phase

Test 1 (a = 1.3 mm, s = 0.15 mm/rev, v = 415 m/min)

Test 2 (a = 1.5 mm, s = 0.1 mm/rev, v = 450 m/min)

Test 3 (a = 1.0 mm, s = 0.2 mm/rev, v = 400 m/min)

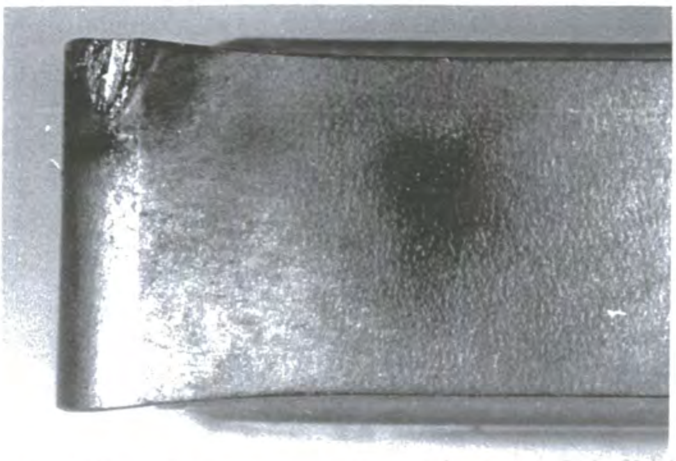
A. TP10 inserts used for finishing EN8 steel (Table 5.1)

Test 2 (a = 1.1 mm, s = 0.19 mm/rev, v = 390 m/ min)

Test 3 (a = 1.5 mm, s = 0.2 mm/rev, v = 395 m/min)

Test 4 (a = 0.7 mm, s = 0.23 mm/rev, v = 450 m/min)

B. TP20 inserts used for finishing EN8 steel (Table 5.3)



Test 2 (a = 2.0 mm, s = 0.2 mm/rev, v = 330 m/min)

Test 3 (a = 1.7 mm, s = 0.25 mm/rev, v = 310 m/min)

Test 4 (a = 1.6 mm, s = 0.28 mm/rev, v = 295 m/min)

C. TP20 inserts used for semi-roughing EN8 steel (Table 5.5)

Test 1 (a = 3.0 mm, s = 0.25 mm/rev, v = 150 m/min)

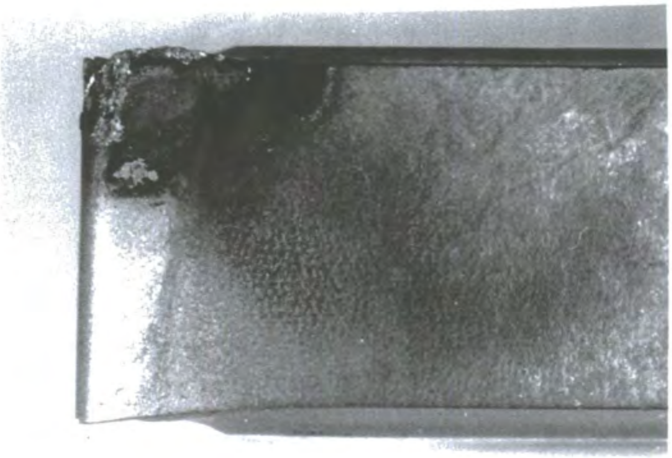
Test 2 (a = 3.0 mm, s = 0.3 mm/rev, v = 125 m/min)

Test 4 (a = 3.0 mm, s = 0.4 mm/rev, v = 110 m/min)

D. TP35 inserts used for semi-roughing SS316 stainless steel (Table 5.7)

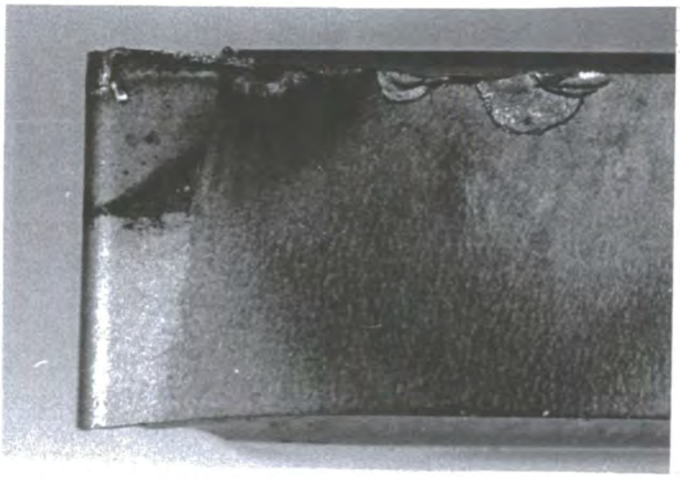
Test 2 (a = 0.5 mm, s = 0.24 mm/rev, v = 490 m/min)

Test 4 (a = 0.8 mm, s = 0.22 mm/rev, v = 410 m/min)

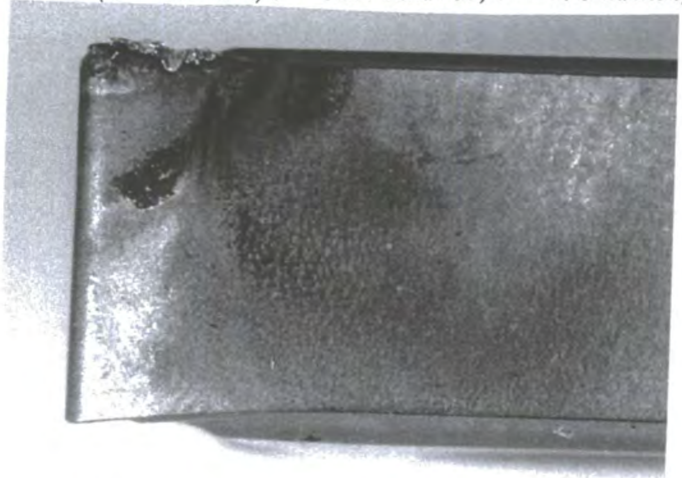


Test 5 (a = 1.5 mm, s = 0.18 mm/rev, v = 430 m/min)

A. TP10 inserts used for finishing EN8 steel (Table 8.1)



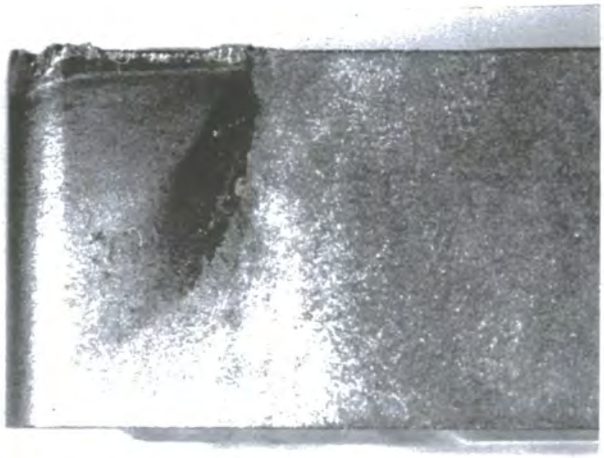
Test 1 (a = 0.5 mm, s = 0.24 mm/rev, v = 470 m/min)



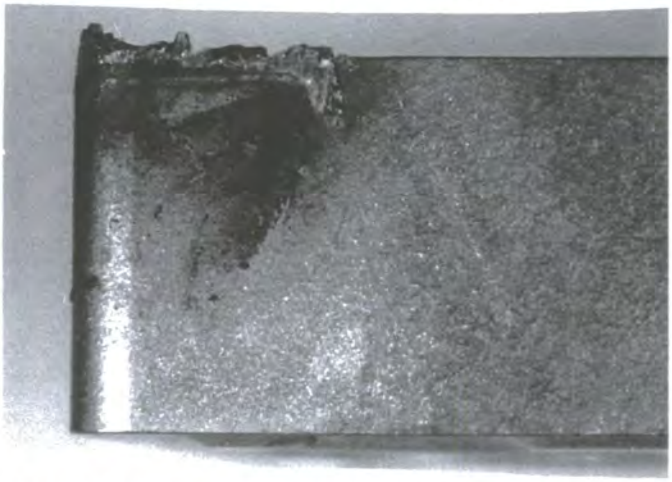
Test 3 (a = 1.4 mm, s = 0.17 mm/rev, v = 360 m/min)

Test 4 (a = 0.9 mm, s = 0.21 mm/rev, v = 410 m/min)

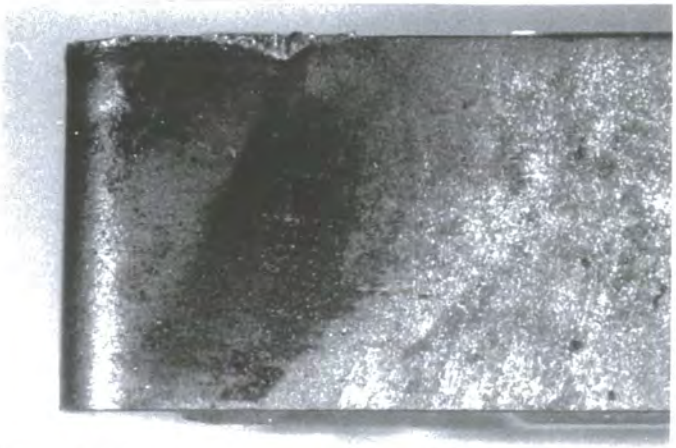
B. TP20 inserts used for finishing EN8 steel (Table 8.2)



Test 2 (a = 1.9 mm, s = 0.23 mm/rev, v = 320 m/min)

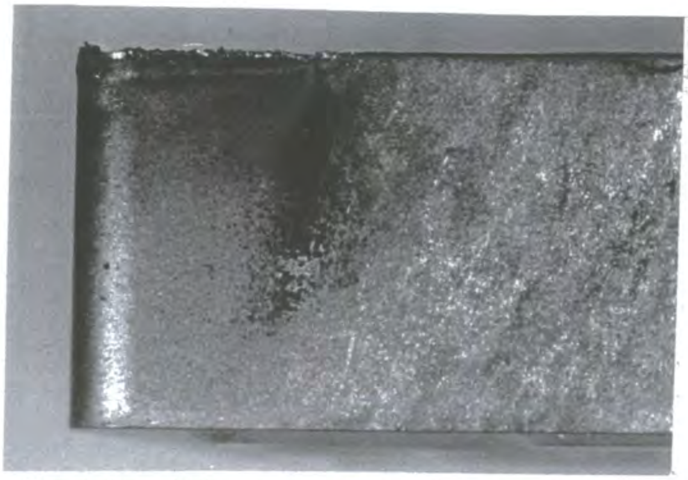


Test 3 (a = 1.7 mm, s = 0.26 mm/rev, v = 305 m/min)



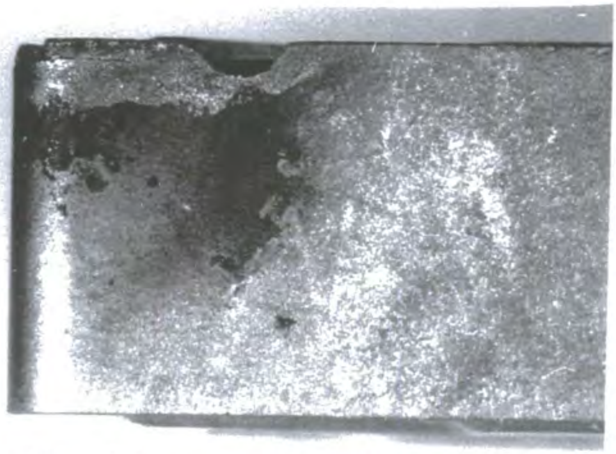
Test 5 (a = 1.8 mm, s = 0.24 mm/rev, v = 315 m/min)

C. TP20 inserts used for semi-roughing EN8 steel (Table 8.3)



Test 1 (a = 3.0 mm, s = 0.3 mm/rev, v = 140 m/min)

Test 2 (a = 3.0 mm, s = 0.25 mm/rev, v = 120 m/min)



Test 3 (a = 3.0 mm, s = 0.4 mm/rev, v = 100 m/min)

D. TP35 inserts used for semi-roughing SS316 stainless steel (Table 8.4)