CHAPTER 2

2. Background to machining and tool wear

2.1 Introduction

In this chapter, the basics of metal cutting and tool failure are explored. Tool failure refers to the wear *and / or* the catastrophic breakage of tools. Selecting proper operating conditions can prevent catastrophic tool failure. With present technology, tool wear cannot be prevented. At some stage the tool will wear out and will require replacement. For the purpose of this study, the failure of single point turning tools are discussed, although the failure of tools used for processes like milling and drilling are similar. These tool types are called defined cutting edges because the exact geometry of the tool is known. A grinding wheel is an example of a non-defined cutting edge, because the geometry of the cutting edge was randomly generated. The mechanics of cutting with defined cutting edges are often similar. It is believed that many of the concepts proposed in this research can possibly be extended to other machining processes with defined cutting edges, even if these are not single point tools.

Machine tool failure is described in terms of failure mechanisms and modes. The failure mechanism is the underlying cause of the tool failure, whereas the failure modes are used to describe the nature or the appearance of the failure. The wear mechanisms and wear modes are covered in detail in this chapter. Some other relevant aspects like tool wear maps and mathematical models for tool life are also discussed as relevant background material.

2.2 Mechanics of the cutting process

2.2.1 Introduction

This section will cover an introduction to the mechanics of turning, starting with the basic principles of orthogonal and oblique cutting (refer to the textbook by Altintas [14] from which some information presented in this section was sourced). Although most common cutting operations are three-dimensional, the simple two-dimensional case of orthogonal cutting is useful to introduce the mechanics of metal cutting. The mechanics of more complex three-dimensional cutting operations are usually determined by applying a transformation model to orthogonal or oblique models.

2.2.2 Orthogonal cutting

A schematic representation of orthogonal cutting is depicted in Figure 2.1 (adopted from [14]). Orthogonal cutting is a process where metal is removed with a straight tool with the cutting edge perpendicular to the cutting velocity V. A metal chip with width b and depth h is sheared away from the workpiece with speed V_c. The cutting is assumed to be uniform and therefore it is modelled as a plane strain deformation process. In the case of orthogonal cutting the forces are exerted only in the direction of velocity and uncut chip thickness, called the tangential F_t and the feed force F_f.

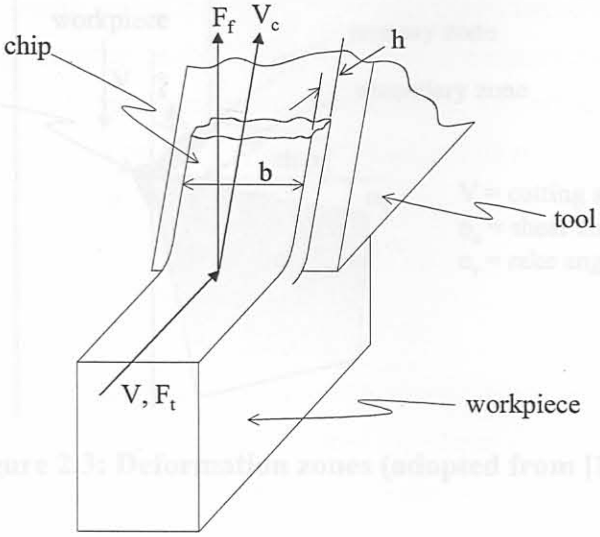


Figure 2.1: Orthogonal cutting geometry (adopted from [14])

2.2.3 Oblique cutting

In oblique cutting the cutting edge is orientated with an inclination angle and an additional third force, the radial force F_r, act in the radial direction. The geometry of oblique cutting is depicted in Figure 2.2 (adopted from [14]). During oblique cutting, the chip is sheared away from the workpiece with an angle η, called the chip-flow angle. The angle i between the workpiece and the cutting edge, is referred to as the cutting edge inclination angle.

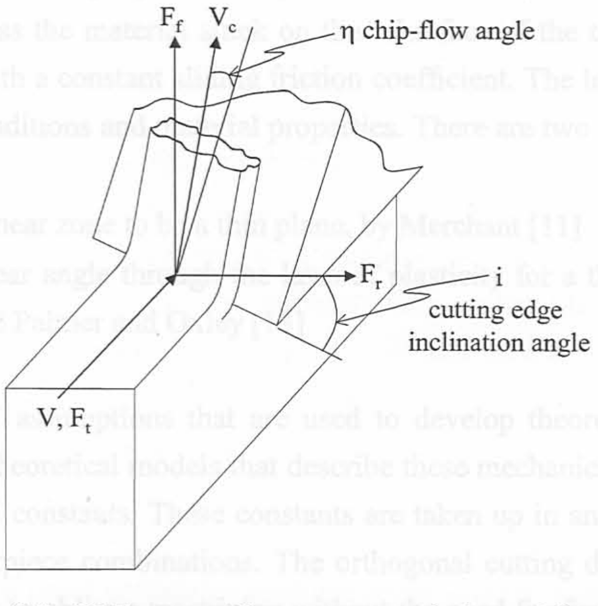


Figure 2.2: Oblique cutting geometry (adopted from [14])

There are three basic deformation zones formed during metal cutting, as shown in the cross-sectional view in Figure 2.3 (adopted from [14]). Stabler [10] found that the orthogonal angle is the same as the chip flow angle for orthogonal cutting (hence $\eta = i$). This is called Stabler's empirical chip flow rule and applies to many machining operations.

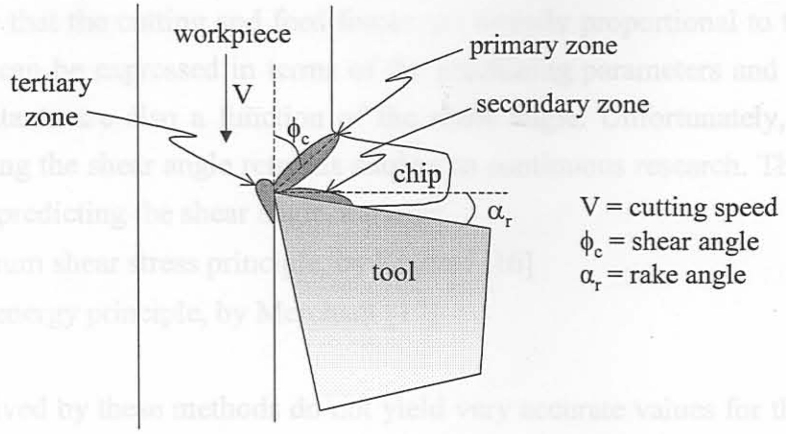


Figure 2.3: Deformation zones (adopted from [14])

When the tool tip penetrates the workpiece, workpiece material is sheared over the primary shear zone to form the chip. The sheared material partially deforms as the chip moves over the rake face of the tool in the secondary shear zone. The area where the flank face of the tool rubs along the newly machined surface is the tertiary shear zone. This is also referred to as the *friction zone* because the flank of the tool rubs against the newly machined surface. The chip initially sticks to the rake face of the tool in the *sticking zone*. A number of theoretical equations exist that describe the mechanics in the three deformation zones. See also for example the descriptions in reference [14].

The friction stress is approximately equal to the yield shear stress of the material at the sticking zone where the chip moves across the material stuck on the rake face of the tool. The chip will then stop sticking and start sliding with a constant sliding friction coefficient. The length of the contact zone depends on the machining conditions and material properties. There are two approaches for analysing the primary shear zone:

- Assuming the shear zone to be a thin plane, by Merchant [11]
- Predicting a shear angle through the laws of plasticity for a thick shear zone, by Lee and Shaffer [12] and Palmer and Oxley [13]

These are the fundamental assumptions that are used to develop theoretical models of the cutting forces. In many cases, the theoretical models that describe these mechanics still require experiments to determine certain empirical constants. These constants are taken up in an orthogonal cutting database for different tool and workpiece combinations. The orthogonal cutting database can then be used in extended models that apply to oblique machining without the need for further experiments. A description of these methods and equations is not within the scope of this text, but can be found in references such as [14,15]. The main problem with this approach is the infinite number of tool and workpiece combinations, and also the somewhat complex nature of the formulations. As a result, the methods are not often implemented to verify cutting force measurements and are of limited to use to industry.

Another approach is mechanistic modelling, which can assist to determine the 3-D cutting forces for any practical tool and workpiece combination. With this method, a specific cutting pressure constant (K_t) and a feed pressure constant (K_f) must be determined experimentally. The underlying assumption of this approach is that the cutting and feed forces are directly proportional to these constants. Hence, the cutting forces can be expressed in terms of the machining parameters and the pressure constants. The pressure constants are also a function of the shear angle. Unfortunately, an accurate analytical method of predicting the shear angle remains subject to continuous research. There are two fundamental approaches for predicting the shear angle, namely:

- The maximum shear stress principle, by Krystof [16]
- Minimum energy principle, by Merchant [17]

The equations derived by these methods do not yield very accurate values for the shear angle, but provide a meaningful insight into the relationship between the shear angle, rake angle (refer Figure 2.3) and the friction coefficient of a tool and workpiece combination. The aim of tool design would be to keep the shear angle as small as possible to keep power consumption and cutting forces low. The rake angle must be at a maximum and a cutting fluid must be used to decrease the friction coefficient. By applying one of the assumptions stated above, the oblique cutting parameters can be solved and will provide a model to determine cutting forces.

There are also a number of empirical models, and the one proposed by Armarego is probably the most famous [14]. This approach assumes that the shear velocity is collinear with the shear force, and that the chip length ratio in oblique cutting is the same as for orthogonal cutting. If the Stabler rule is applied, the chip flow, shear and the normal friction angle can be used in an empirical or mechanistic model to solve cutting forces.

2.3 Turning

Turning is one of the oldest and simplest machining processes, and is used to machine cylindrical parts. During turning, a workpiece is clamped in a chuck that is fixed to a spindle. Long workpieces are held in the chuck and the centre of a tailstock. A single point tool is clamped on a tool post, and the tool post can move between the spindle and the tailstock. Conventional lathes have only one motor at a constant speed, and the speed is transmitted to the spindle and feed drive gearboxes with belts. The feed and speed can be changed with marked shift handles that are connected to the respective gearboxes. In modern CNC lathes the speed and feed can programmed numerically, because these have stepless computer controlled drives.

CNC lathes generally have a turret containing multiple tools, and the turret can often move along two axes. If the tool moves along the axis of the spindle, it will reduce the diameter of the workpiece and this is referred to as turning. If it moves perpendicular to the main axis, it will remove material along the flat face of the workpiece, in what is called a facing or parting operation. These are external turning operations. When metal is removed from the inside of a cylindrical workpiece, it is called internal turning or boring. With this combination of movements, a lathe can be used to machine many complex cylindrical parts, and can also be used to produce a screw thread. Often, roughing and finishing operations are performed to achieve a certain surface quality. A sketch of a typical turning operation is shown in Figure 2.4. The most important machining parameters are the:

- cutting speed [V] usually expressed in m/min
- feed [f] rate usually expressed in mm/rev
- depth of cut [doc] usually expressed in mm

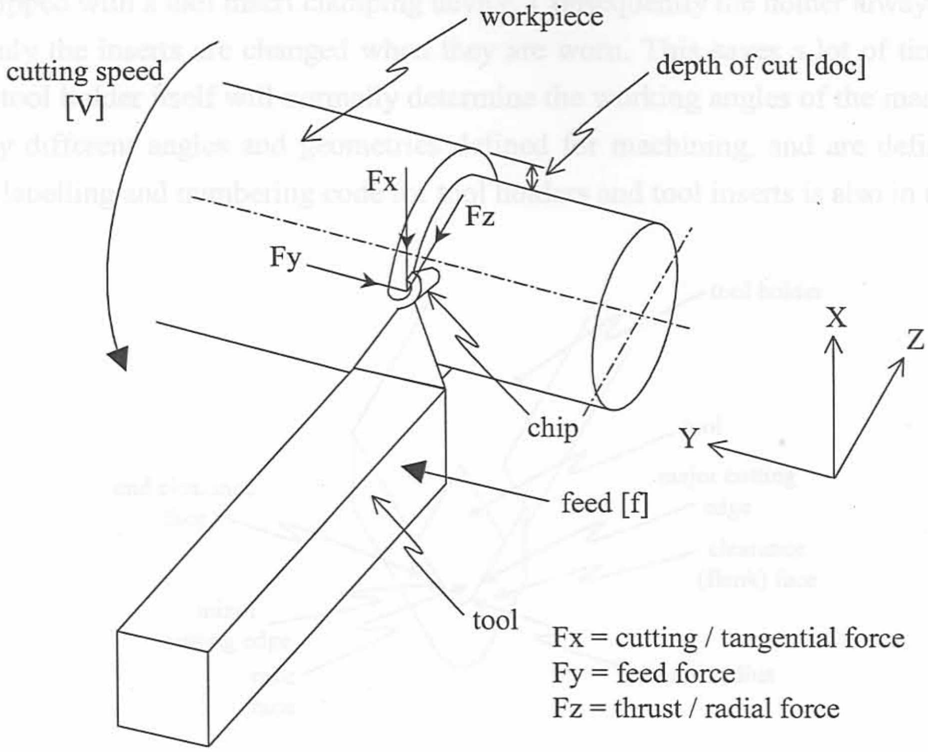


Figure 2.4: Diagrammatical turning operation

The cutting speed is defined by:

$$V = \pi D n \text{ [m/min]} \tag{2.1}$$

The feed rate is defined by:

$$f = \frac{lm}{n} \text{ [mm/rev]} \tag{2.2}$$

A total cutting time can also be determined, expressed as:

$$T = \frac{L}{n \times f} \text{ [min]} \tag{2.3}$$

where:

D = workpiece diameter [mm]

n = rotational speed of spindle [rpm]

lm = cutting length per minute [mm/min]

L = length of cut along shaft [mm]

The force response on the tool tip as a result of the turning operation is the three component cutting force, as shown in Figure 2.4. Turning is an oblique machining operation and hence these forces can be predicted by transforming the orthogonal cutting parameters to an oblique turning geometry using a conversion of the operational angles. Turning causes varying chip thickness and thus the angle transformation is applied separately to a region of uniform thickness and a region of varying thickness. The mechanistic method discussed before is a frequently used to model the cutting forces for turning. It should be kept in mind that such a model will only apply to the static cutting forces.

Basic terminologies for turning tools are shown in Figure 2.5. Turning tools often consist of a standard tool holder equipped with a tool insert clamping device. Consequently the holder always remains in the machine and only the inserts are changed when they are worn. This saves a lot of time in setting up machines. The tool holder itself will normally determine the working angles of the machining process. There are many different angles and geometries defined for machining, and are defined by the ISO 3002/1 [18]. A labelling and numbering code for tool holders and tool inserts is also in use worldwide.

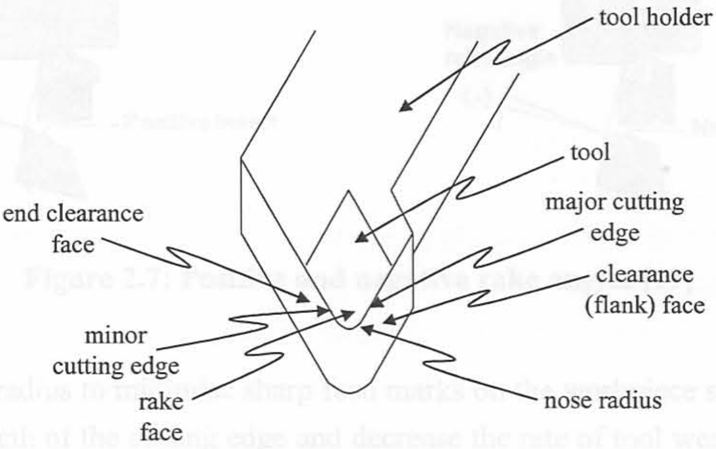


Figure 2.5: Turning tool terminologies

The basic geometries for a turning tool are depicted in Figure 2.6. The important parameters are the tool nose radius, rake and side cutting edge angles. It was noted that different terms are sometimes used for the same angles in the literature. In this document, the terms defined in Figure 2.6 will be used, which also corresponds to ISO 3002/1.

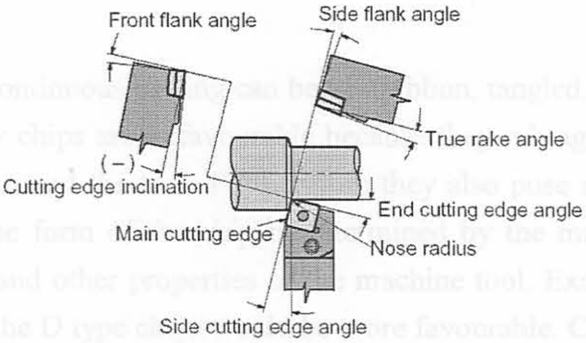


Figure 2.6: Basic angles for turning [19]

The ISO also separates between working angles and tool angles, the working angles being those that are used when the tool is in operation, and the tool angles being those of the tool entity itself. It is important to understand the influences of the main geometries on the turning operation with relevance to tool wear.

The chip lands and slides on the rake face of the tool, and the rake angles will determine the direction of the chip flow. Instead of the normal rake angle, a definition of a side and a back rake angle is often used. In orthogonal cutting, there is no back rake angle, and only a side rake angle is considered. Depending on the rake angles, tools are called positive, neutral or negative. Positive inserts produce higher shear angles and reduce cutting forces. Negative inserts produce higher forces but is useful in interrupted cutting due to their higher shock resistance, since the initial contact with the workpiece material is away from the weak cutting edge. The chip flow will be more towards the workpiece. This is depicted in Figure 2.7.

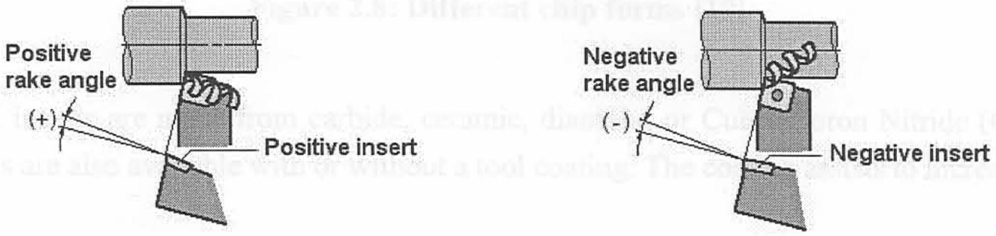


Figure 2.7: Positive and negative rake angles [19]

Tool tips have a small radius to minimise sharp feed marks on the workpiece surface. Increased radius also increases the strength of the cutting edge and decrease the rate of tool wear. However, a too large nose radius is also not advisable because it makes the tool susceptible to self-excited vibrations and also causes poor chip control. The theoretical surface roughness (R_t) is expressed as (also refer to Appendix I):

$$R_t = \frac{f^2}{8 \times r} \times 1000 \quad [\mu\text{m}] \qquad (2.4)$$

where:

f = feed rate [mm/rev]

r = nose radius [mm]

The chips produced during continuous turning can be of a ribbon, tangled, corkscrew, spiral or comma type. Tangled and corkscrew chips are unfavourable because they rub against the finished workpiece and can become entangled around the tool. Furthermore they also pose a danger to the operator and can cause tool breakage. The form of the chip is determined by the machining parameters, cutting fluid, material combination and other properties of the machine tool. Examples of different chips are shown in Figure 2.8, where the D type chips would be more favourable. Chip breakers can be clamped on tool holders or formed on tool inserts to assist in breaking long chips. They force the chip to curl toward the workpiece or tool, thus creating a large tensile stress that leads to breakage of the chip.

Jawahir *et al.* [20] investigated the effects of chip flow on tool wear with chip breaker type tools. It was found that the failure of these tools is generally due to improper groove utilisation, and hence the tool, machine and work material must be taken into account to evaluate the performance of these tools. A knowledge-based approach for designing chip breakers is suggested by Jawahir and Fang [21], taking the above-mentioned considerations into account. Other studies related to modelling the chip formation with analytical and numerical methods can be found in [22-29].

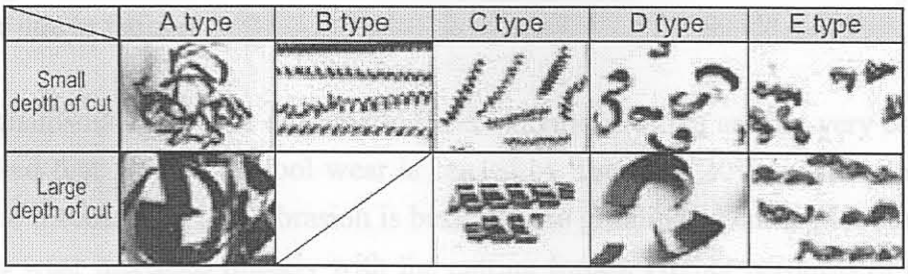


Figure 2.8: Different chip forms [19]

Turning tool inserts are made from carbide, ceramic, diamond or Cubic Boron Nitride (CBN). Many other variants are also available with or without a tool coating. The coating assists to increase tool life.

Another important phenomenon to turning operations is chatter vibrations. Chatter is self-excited vibration resulting from the generation of different chip thickness during machining. Initially, cutting forces excites a structural mode of the machine-workpiece system. This will leave a wavy surface finish on the workpiece. During the next revolution another wavy surface will be made in the same way. Depending on the phase shift between these two waves, the maximum chip thickness can grow and oscillate at a particular frequency that is close to a structural mode. This is called the regenerative chatter frequency [14]. Chatter cause a poor surface finish and can also lead to tool breakage. The analysis and prediction of chatter has been the subject of research for many years. Morimoto *et al.* [30] developed a piezoelectric shaker / actuator to regenerate the vibrations of the cutting process. In this way, unwanted vibrations such as chatter can be attenuated. The system is also helpful to determine the dynamic properties of the machine tool. Koizumi *et al.* [31] used a very interesting approach called the correlation integral in the time domain to identify chatter onset. Lägo *et al.* [32] designed a sensor and actuator integrated tool for turning and boring to control chatter. The tool holder shank vibrations are supplied to the actuator via a digital controller. An adaptive feedback control system is used to perform broadband vibration attenuation up to 40dB at different frequencies simultaneously.

2.3 Tool wear

2.3.1 Tool failure mechanisms

It is important to identify tool failure mechanisms in order to select appropriate machining parameters, and also for interpretation of the sensor signals during wear monitoring. If the underlying mechanisms are understood, phenomena in the sensor data can be attributed to certain tool failure mechanisms and modes. Mechanical loads, thermal loads, chemical reactions and abrasive loads, cause tool wear. The cutting conditions and the tool and workpiece materials influence these loads. The different loads can cause certain wear mechanisms, and depending on the loads, they may occur in combination. These mechanisms have either a physical or chemical characteristic that cause loss or deformation of tool material. Tool wear mechanisms can be classified into several types, summarised as follows [33]:

- abrasive wear resulting from hard particles cutting action
- adhesive wear associated with shear plane deformation
- diffusion wear occurring at high temperatures
- fracture wear due to fatigue

Other wear mechanisms are plastic deformation and oxidation, which are not very common in industry. It is estimated that 50% of all tool wear is caused by abrasion, 20% by adhesion, and the other 10% by other the mechanisms [3]. Abrasion is basically the grinding of cutting tool material. The volume of abrasive wear increases linearly with the cutting forces. Higher hardness of the tool material can reduce abrasive wear. During adhesion the high pressures and temperatures on the roughness peaks on the tool and the workpiece cause welding. These welding points are broken many times every second and cause removal of the tool material. Diffusion wear occurs at even higher cutting speeds where very high temperatures are present (especially when using hard metal tools).

2.3.2 Tool failure modes

Tool wear will generally occur as a combination of a number of wear modes, with one mode predominant. The dominant mode will depend on the dominant wear mechanism. For a given tool and workpiece combination, the dominant wear mode can be determined at different cutting speeds using the product of the cutting speed and the undeformed chip thickness [34]. The common wear modes are:

- flank wear
- crater wear
- chipping
- breakage
- nose wear
- plastic deformation
- cracking
- notch wear

The basic interpretations of causes, mechanisms, types and consequences of tool wear are summarised in Figure 2.9 (adapted from [34]). The consequences of tool wear are deviations in shape and roughness of the machined part, which cause the part to be discarded because it is out of the allowable tolerance. Figure 2.10 is a graphical representation of the different tool failure modes. Although they are shown separately in the figure, they can also occur in combinations, *e.g.* flank wear and notching. The most widely researched tool failure modes for turning with single point tools are flank wear, breakage and crater wear. Flank and crater wear are generally accepted as the normal tool failure modes, because the other failure modes can be avoided by selecting the proper machining parameters. In fact, it has also been shown that crater wear can also be avoided by selecting sufficiently low feed rate and cutting speed [35]. The growth of flank and crater wear is directly related to the cutting time (or length of cut), unlike some of the other failure modes, which can occur unexpectedly, even with a new tool. It is already well established that flank wear generally has the greatest influence on the workpiece dimensions and surface quality [36]. For this reason ways to predict flank wear has been the pursuit of researchers for many years. However, hard metal tools such (*e.g.* synthetic diamond) sometimes exhibit other dominant failure modes that affect workpiece quality [37], and it is thus of importance to comprehend the mechanics of the different failure modes.

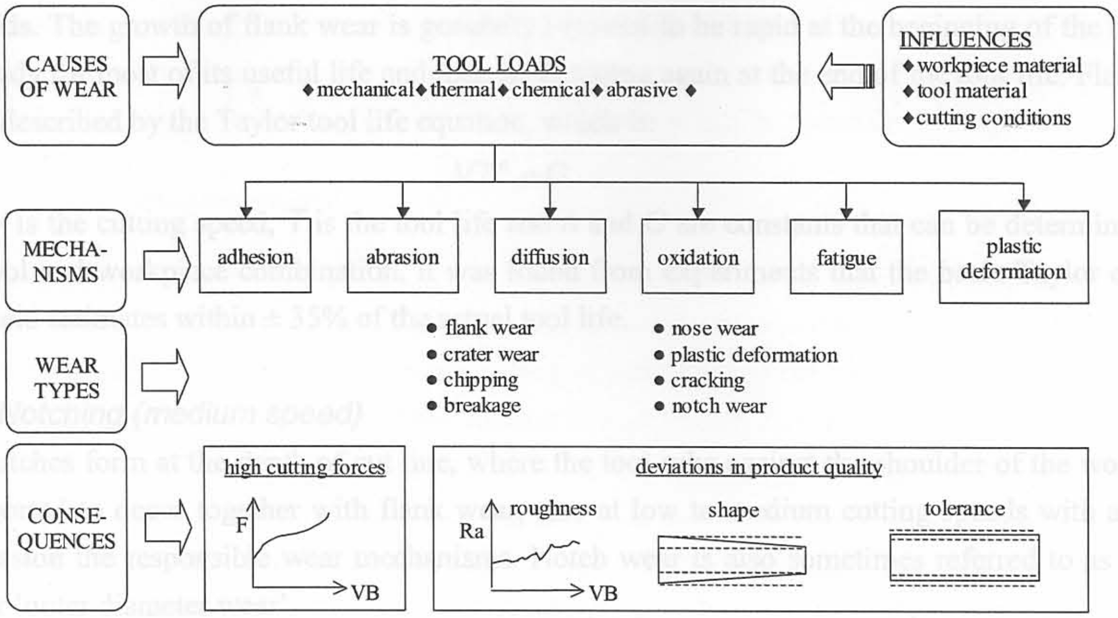


Figure 2.9: Causes, mechanisms, types and consequences of tool wear (adapted from [34])

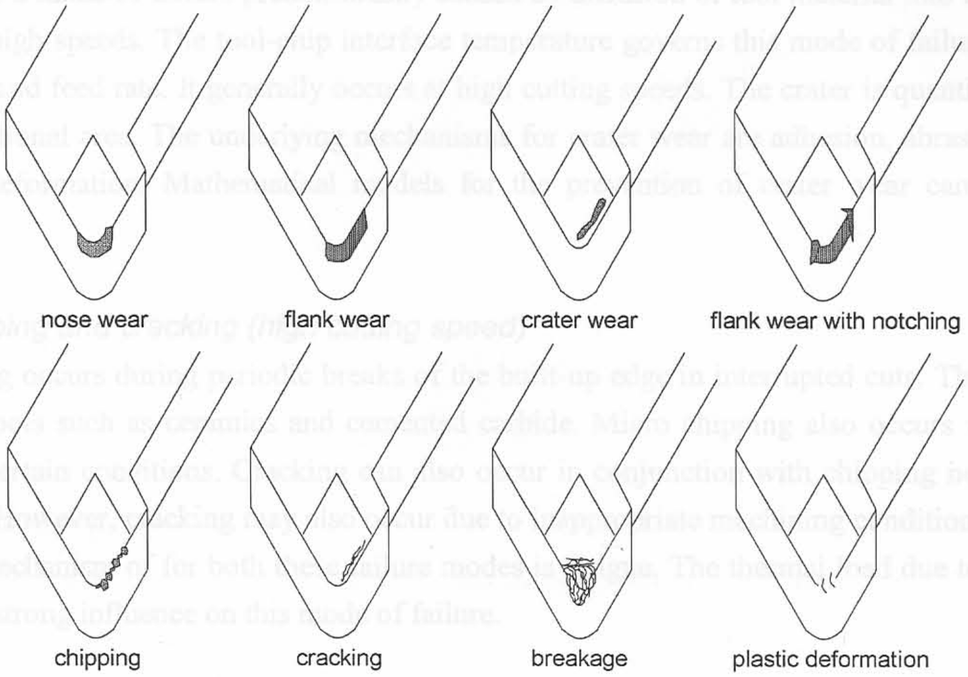


Figure 2.10: Tool failure modes

A. Nose wear (low speed)

Nose wear or edge rounding occurs through the abrasion wear mechanism on the major edges of the tool. Nose wear is caused by the selection of inappropriate cutting conditions and occurs on the tool tip at low cutting speeds.

B. Flank wear (medium speed)

Flank wear is the volumetric loss at the top of the tool edge, and is mainly caused by abrasion. Some authors affirm that the flank wear in coated tools first occurs due to abrasion, and at a later stage of tool life adhesion and diffusion also occurs [38]. Flank wear normally occurs at medium to low operating speeds. The growth of flank wear is generally reported to be rapid at the beginning of the tool life, then steady for most of its useful life and then accelerating again at the end of the tool life. Flank wear is often described by the Taylor tool life equation, which is:

$$VT^n = C \tag{2.5}$$

where V is the cutting speed, T is the tool life and n and C are constants that can be determined for a given tool and workpiece combination. It was found from experiments that the basic Taylor equation could yield estimates within ± 35% of the actual tool life.

C. Notching (medium speed)

Wear notches form at the depth of cut line, where the tool rubs against the shoulder of the workpiece. It is reported to occur together with flank wear, also at low to medium cutting speeds with adhesion and abrasion the responsible wear mechanisms. Notch wear is also sometimes referred to as 'groove wear' or 'outer diameter wear'.

D. Crater wear (high speed)

Crater wear is a mode of failure predominantly caused by diffusion of tool material into the chip when operating at high speeds. The tool-chip interface temperature governs this mode of failure, influenced by the speed and feed rate. It generally occurs at high cutting speeds. The crater is quantified by depth and cross-sectional area. The underlying mechanisms for crater wear are adhesion, abrasion, diffusion and plastic deformation. Mathematical models for the prevention of crater wear can be found in [39,40].

E. Chipping and cracking (high cutting speed)

Edge chipping occurs during periodic breaks of the built-up edge in interrupted cuts. This is common with brittle tools such as ceramics and cemented carbide. Micro chipping also occurs with diamond tools under certain conditions. Cracking can also occur in conjunction with chipping near the end of the tool life. However, cracking may also occur due to inappropriate machining conditions. The underlying wear mechanism of for both these failure modes is fatigue. The thermal load due to high cutting speeds has a strong influence on this mode of failure.

F. Plastic deformation (very high speed)

Plastic deformation is both a failure mechanism and failure mode. Plastic deformation starts when the temperature of the tool tip reaches a certain value. This implies that the tool yield strength is lowered below the existent normal stress. Further plastic deformation results in a temperature increase that causes complete failure. Mathematical models for the prevention of plastic deformation wear can be found in [39,40].

G. Breakage (very high speed)

Tool breakage or fracture is a mode of failure characterised by breakaway of material on the tool tip. Breakage occurs when the feed-rate is too high, or when a tool is used with too low fracture strength. Either plastic deformation and / or fatigue can be responsible for this mode of failure. It may also occur if a considerable degree of nose wear or severe depths of crater wear is present. Breakage is common with brittle tools such as ceramics and CBN. Breakage will normally occur at very high cutting speeds, but may also occur at lower speeds if an inappropriate tool material is selected for a certain task. Mathematical models for the prevention of tool breakage can be found in [39,40].

2.3.3 Tool wear measurement

The quantification of tool wear can be a very subjective matter due to human interpretation of a microscopic picture. In order to be consistent, it is suggested by machine tool developers that the same person perform all the wear measurements during experiments. Wear measurement of tools is done through the implementation of ISO 3685, summarised in Figure 2.11 for turning (after Dimla [41]). Flank wear is quantified in terms of VB, which is the mean of the wear height on the tool flank. The length of flank wear is also measured in terms of b. The maximum flank wear is VB_{max}. The notch wear can also be measured (if notch wear is present), in terms of VB_{notch}. Crater wear is quantified in terms of the crater depth K_T, and sometimes also the distance between the cutting edge and crater centre, quantified in terms of K_M.

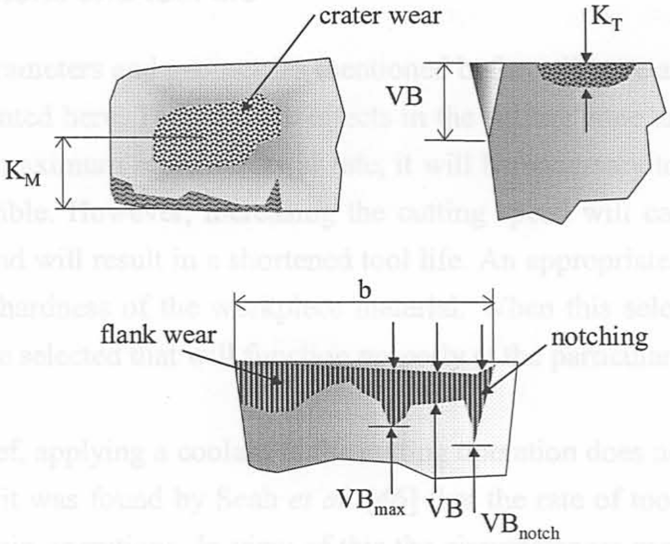
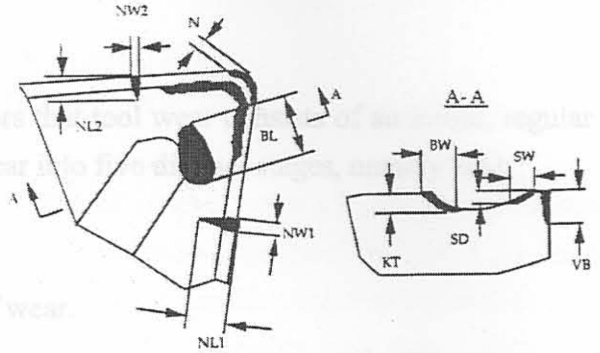


Figure 2.11: Convention for tool wear quantification (ISO 3685 after [41])

Sometimes other wear parameters are used. Recently, a method for measuring the wear for grooved tools was suggested by Jawahir *et al.* [42,43]. The suggested method has become standard practise in research for assessing wear with coated grooved tools. These parameters are shown in Figure 2.12. It should also be mentioned here that Jawahir *et al.* [44] extended their work with grooved tools in developing an equivalent toolface model. In essence, an equivalent flat toolface can be determined for grooved tools. The equivalent toolface can then be used to predict certain wear and failure modes of the grooved tools. Parakkal *et al.* [45] also proposed a mechanistic model for modelling the cutting forces during turning with grooved tools.



VB	flank wear	*N*	nose wear
BW	width of groove backwall wear	NL_1	notch wear length on main cutting edge
BL	length of groove backwall wear	NW_1	notch wear width on main cutting edge
KT	depth of groove backwall wear	NL_2	notch wear length on secondary cutting edge
SW	width of secondary face wear	NW_2	notch wear width on secondary cutting edge
SD	depth of secondary face wear		

Figure 2.12: Tool wear parameters for grooved tools [42]

2.3.4 Machining conditions and tool life

The various machining parameters and geometries mentioned before all have an effect on tool life, and a short discussion is presented here. Temperature effects in the cutting zone and in the tool itself govern tool life. To enable a maximum metal removal rate, it will be necessary to use the highest cutting speed and feed rates possible. However, increasing the cutting speed will cause increasing temperatures in the cutting zone and will result in a shortened tool life. An appropriate cutting speed should be selected according to the hardness of the workpiece material. When this selection is made, a certain grade of tool insert must be selected that will function properly at the particular cutting speed.

In contrast to popular belief, applying a coolant to the cutting operation does not necessarily reduce the rate of tool wear. In fact, it was found by Seah *et al.* [46] that the rate of tool wear increases when a coolant is applied for certain operations. In view of this the circumstances must be evaluated properly before a coolant is applied by default. Feed rate does not have a large influence on tool life, but there is a certain feed rate for optimal tool life for each operation.

Depth of cut also does not have such a large influence on the tool life compared to cutting speed. The depth of cut must be determined according to the required stock removal, shape of the workpiece and also rigidity of the machine and workpiece. A very small depth of cut causes friction and will shorten tool life. The rake angle also influences tool life. Positive rake angles can increase tool life but can only be used in certain applications. The side cutting edge angle (lead angle) can lower the impact on the tool and has an effect on the cutting forces. Increasing the side cutting edge angle increases chip contact length and decreases chip thickness. The result in that the cutting force is dispersed over a larger area and the tool life is prolonged. However, chip control and breakage is more difficult to achieve with increasing side cutting edge angle. Furthermore, it will increase the thrust forces and as a result cannot be used with long or slender workpieces.

2.3.5 Tool wear stages

It is assumed by most authors that tool wear consists of an initial, regular and fast wear stage [47,48]. Some authors divide tool wear into five distinct stages, namely [38]:

1. Initial stage of wear.
2. Regular stage of wear.
3. Micro-breakage stage of wear.
4. Fast wear stage.
5. Tool breakage.

It has been established by various researchers that the initial and fast (before tool breakage) stages wear occur more rapidly than the regular stage. A reason for this behaviour is very seldom given. Bonifacio and Diniz [38] explained that during the fast wear stage with coated carbide tools, the tool loses its coating and the tool substrate (which has less resistance) begins to perform the cut. During the initial stage, the tool edge loses its radius quickly and after which the process stabilise for a given amount of time. Lim [49] found that with a tungsten carbide tool the initial wear rate is also faster due to the breakage of the sharp cutting edge after which a finite wear land forms. Flank wear in relation to time or length of cut will typically appear as depicted in Figure 2.13. From the literature it is unclear if failure modes other than flank wear display this kind of behaviour.

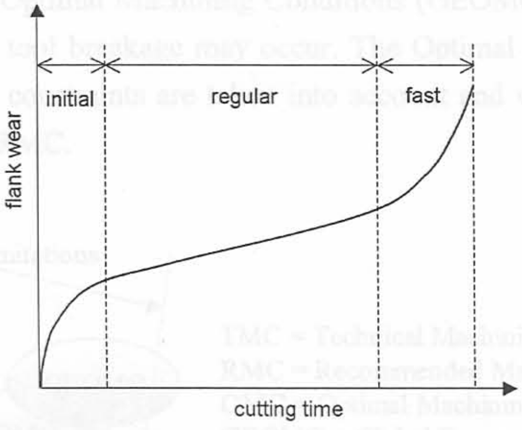


Figure 2.13: Flank wear in relation to cutting time

The wear rate is in fact a function of the wear mechanisms, and therefore any increase or decrease in the wear rate must be accounted for by investigating the wear mechanisms. The abrasion and adhesion mechanisms cause flank wear, and the cutting temperature influences the mechanisms. Increasing tool wear also cause an increase in the cutting temperature. This in its turn can cause increased activity of the abrasive and adhesive wear mechanisms, and could be the reason for increased wear rates near the end of tool life.

2.4 Tool wear mapping

2.4.1 Introduction

In order to optimise a metal removal process with a tool wear constraint, engineers must have ready access to information pertaining to the wear process of interest. User-friendly databases must be established to provide appropriate information for the choice of optimal operating conditions for a given set of materials. The best approach to present complex wear data is through a wear map. Such a map can provide a multi-dimensional graphical presentation of wear data. Different types of wear maps exist, such as wear-mode, wear-transition, wear-regime and wear-mechanism maps. The wear-mode map is the most common, where regions of the dominant wear mode are given for a range of operating conditions. Of course, wear-mode maps are not only useful for TCM. Wear maps are commonly used for the optimisation of a machining process and during the development of adaptive control systems for machine tools. This section will discuss a few examples of tool wear mapping.

An operating conditions map given by Lundholm [50] is reconstructed in Figure 2.14. The figure maps the different regions of operating conditions for ranges of feed rate and speed. The Technical Machining Conditions (TMC) is bounded only by the technical performance of the machine tool. The supplier of the tool will also state the Recommended Machining Conditions (RMC), which is in a conservative safety zone. If the process is economically optimised without taking the technical constraints into account, the Global Economical Optimal Machining Conditions (GEOMC) are found. However, in this region, excessive tool wear or tool breakage may occur. The Optimal Machining Conditions (OMC) can be computed when all the constraints are taken into account and will be safer than the GEOMC and more economical than the RMC.

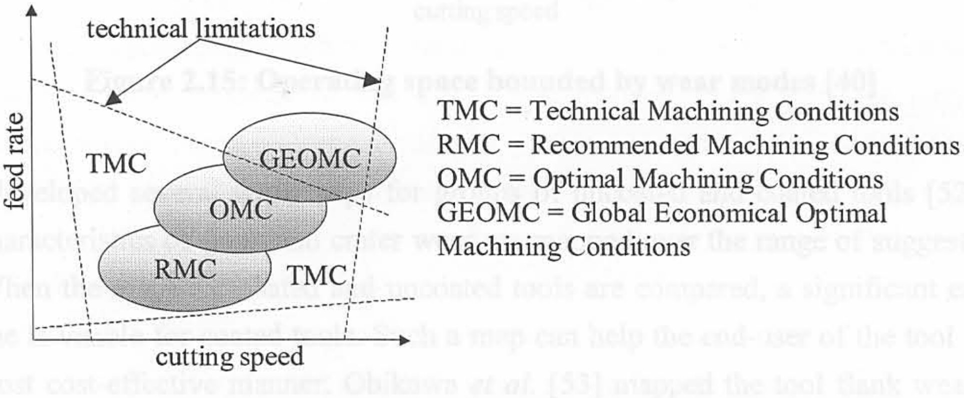


Figure 2.14: Classification of machining conditions [50]

The operating conditions map and wear mode maps are related, because both establish ‘safety zones’ where no excessive tool wear or catastrophic tool failure will occur. Furthermore, the dominant failure mechanisms and modes for a given range of operating conditions can also be determined. This information is very useful for:

- development of TCMS
- optimising of the cutting process

- adaptive control
- prevention of certain failure modes

However, to construct such a map demands a lot of experimental work, and the outcome of the map is very dependant on the tool and workpiece material combination. Especially due to the rapid development of new metals and advancements in machine tool technology, there will probably never be wear-mechanism maps for each and every tool and workpiece combination.

2.4.2 Wear map examples

The originator of graphical representation of tool wear data can be traced to Trent who produced a series of machining charts in the late 1950s [51]. The concept of these diagrams did not capture any further attention until Yen and Wright [40] proposed a map for turning tools. Yen and Wright constructed wear maps based on mathematical models. A reconstructed example of a tool wear map by them is shown in Figure 2.15. Lever *et al.* [39] produced very similar graphs to determine operational zones for the development of a machine learning system. The same types of analytical equations were used to construct the operational zones.

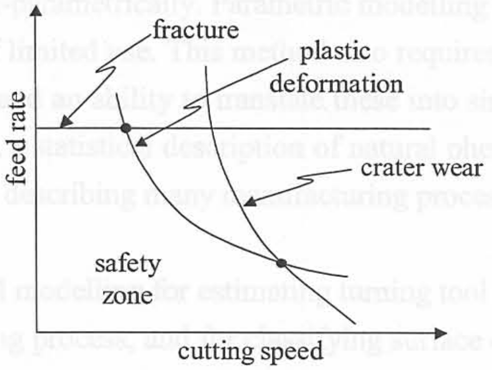


Figure 2.15: Operating space bounded by wear modes [40]

Researchers developed several wear maps for groups of uncoated and coated tools [52]. In both instances the characteristics of flank and crater wear are mapped over the range of suggested machining conditions. When the maps for coated and uncoated tools are compared, a significant enlargement of the safety zone is visible for coated tools. Such a map can help the end-user of the tool to employ the tool in the most cost-effective manner. Obikawa *et al.* [53] mapped the tool flank wear of a carbide tool in a 3-D graph to estimate the optimum cutting conditions and monitor the tool wear. In this case, experimental data were used to construct the map. Da *et al.* [54] also constructed tool wear maps for machining process optimisation, using analytical equations for tool wear and process constraints. The models were proved with experimental data. Recent work Li *et al.* [55] proposed a predictive mapping system for tool wear based on a modified tool wear model. The mapping system can predict wear rate maps accurately with cutting speed, feed rate and flank wear as parameters. The limitation of the system is the fact that the diffusion and adhesion constants for the two materials must be known. In order to establish the accuracy of the model, more work on a wider range of materials will be required.

2.5 Mathematical modelling

Mathematical models are very useful to study tool wear. Most models attempt to predict variables such as the cutting forces, temperatures, pressures, chip flow angles *etc*. Another mathematical approach is tool life equations that attempt to predict the life of the tool under certain machining conditions. With respect to TCM, these are referred to as a sensorless approach. The model is thus used without help from on-line sensors.

Three types of models are used, namely analytical (theoretical), computational (numerical) and empirical (experimental) models. Analytical models are useful to study the effects of tool geometry on the various machining parameters, but are too complex to be of any value in a real-time TCMS. The non-linear, stochastic and time invariant nature of machining processes makes theoretical modelling of machining processes very difficult [56]. Due to the complexity, modelling of the physical law representing the metal removal process cannot be performed for most cases.

Empirical models are models generated from experimental data. The output from empirical models is usually one or more empirical constants. These constants are different for every tool and workpiece combination, but are available in the literature for common combinations. Empirical modelling can be performed parametrically or non-parametrically. Parametric modelling usually represents an adaptation of the analytical model and is of limited use. This method also requires the inputs of an expert familiar with the relational mechanisms and an ability to translate these into simple rules [39]. Non-parametric modelling methods are based on a statistical description of natural phenomena. Empirical models have been used with great success for describing many manufacturing processes.

Grabec *et al.* [57] used empirical modelling for estimating turning tool sharpness, for the determination of surface roughness in a grinding process, and for classifying surface quality of paper. Ruiz *et al.* [58] used a multi-sensor empirical approach to estimate tool wear, and identified tool wear with three different empirical identification methods. The use of an analytical model for force reconstruction for wear identification was proposed by Braun *et al.* [59]. The model can also be used for the prediction of chatter onset. Ravindra *et al.* [60] proposed a mathematical model based on multiple regression analysis. The model describes the wear-time and wear-force relationships for turning operations. Good correlation was found between the cutting force and progressive tool wear. Lin *et al.* [61] describe the use of an abductive network for modelling surface roughness and cutting forces for turning. Abductive networks consist of several polynomial functions organised in layers. One advantage of this method is that the optimal network architecture is determined automatically, and requires less iterative work than Neural Networks (NNs).

Jawahir *et al.* [20] reviewed the most common tool-life relationships in 1995. A modified version of this review is presented in Table 2.1. Some problems were identified with these approaches [20]:

- The methods are not adaptable to all the different tool designs and chip-groove configurations that are used in industry, which have a large influence on the tool life.
- The influence of all the machining parameters on the tool life cannot be described in a systematic

manner.

- The methods do not incorporate the knowledge of human experts.

Table 2.1: Tool-life equations (T = tool life in minutes)

no.	***Tool life equation***	***Comments***	***Ref***
1.	Basic Taylor equation: $VT^n = C$ where V = cutting speed n = Taylor's tool life exponent C = empirical constant	Most widely used equation, however, constants C and n only apply for specific tool and workpiece combinations.	[36,49, 62]
2.	Taylor's reference-speed equation: $\left(\frac{V}{V_R}\right) = \left(\frac{T_R}{T}\right)^n$ where V_R is the reference cutting speed for reference tool-life T_R = 1 min.	n only applies to particular tool and workpiece combinations.	[62]
3.	Modified reference-speed equation with coating and groove effects taken into account: $T = T_R W_g \left(\frac{V_R}{V}\right)^{W_c \frac{1}{n}}$ where W_c = coating effect factor W_g = chip-groove effect factor	Same as reference speed equation, but more accurate and adaptable to coating and chip-groove effects.	[54,63]
4.	Extended Taylor equation: $T = \frac{C_2}{V^P f^q d^r}$ where f = feed d = cut depth C_2 = empirical constant	Better accuracy than basic Taylor equation, but requires several tool-life experiments.	[64]
5.	Temperature-based equation: $\theta T^n = C_3$ where θ = tool temperature C_3 = empirical constant	Equation is not feasible for use on the shop floor.	[20]

6.	Colding's equation based on ECT (Equivalent Chip Thickness): $y = K - \frac{(x-H)^2}{4M} - (N_0 - Lx)z$ where $x = \ln(ECT)$ $y = \ln(V)$ $z = \ln(T)$	Many empirical constants, and machining parameters are integrated into single ECT parameter. However, tool life predictions are inconsistent.	[20]
7.	Basic Taylor equation including rake and clearance angle: $C \propto \left[(\cot\beta - \tan\alpha)^n F(\alpha,\beta)^{\frac{1}{\varepsilon}}\right]^{-1}$ where $F(\alpha,\beta)$ is a function of: $\alpha =$ rake angle $\beta =$ clearance angle	A complicated relationship between tool-life and rake / clearance angles.	[20]
8.	Extended Taylor equation including cutting conditions and tool geometry: $T = C_4 V^n f^m d^P r^q s^t i^u j^x$	Require many tool-life tests to determine all the empirical constants.	[20,65, 66]
9.	Extended Taylor equation including cutting conditions and workpiece hardness: $V = \frac{C_5}{T^m f^y d^x (BHN/200)^n}$ BHN = Brinell Hardness Number	It is claimed to be a good approximation for tool-life ranges of 10-60 min.	[20]

Numerical approaches are methods like the Finite Element Method (FEM) and other types of computational simulations. These models are used to predict variables such as temperatures, forces, pressures and stresses in the cutting zone. Lately, many FEM approaches have been developed dedicated to certain machining operations. The FEM has many advantages, such as the fact that it can handle many different machining conditions, materials and geometries. Athavale and Strenkowski [67] recently published an overview of FEM modelling of machining. It is stated that there is a basic disagreement between researchers in the area of FEM modelling of machining. These unresolved issues are:

1. the failure mechanism at work of the workpiece material at the tool cutting edge
2. the stress distribution and frictional relationship at the tool-chip interface
3. the material flow past a rounded cutting edge, tools with wiper inserts or worn cutting tools

As a result simulation results vary close to the cutting edge and tool-chip interface. Further away, there is a good correlation among the results of the various researchers. There are three types of FEM formulations of machining operations:

1. Langranian (mesh is attached to the workpiece)
2. Eulerian (workpiece material is assumed to flow through a meshed control volume)
3. Arbitrary Langranian-Eulerian (utilise both formulations during iteration)

Thermal behaviour and material models are also required for accurate simulations of the cutting mechanics. To model tool wear with a FEM remains subject to continuous research. This is because the wear mechanics are very complex to model. Hence, FEM models are of limited usefulness for TCM. Despite this, FEM models provide the most comprehensive and accurate results compared to other existing techniques. There are many other applications for FEM modelling. Sandstrom [68] proposed a FEM for modelling the physics of high-speed machining. The model can assist in planning manufacturing processes on a sound technical foundation. Lovell *et al.* [69] proposed a FEM model for variable tool-chip interface and tool coatings. This can be used to assist to evaluate optimal tool coating parameters and wear rates. A picture of an explicit dynamic FEM model of the machining process from Lovell *et al.* [69] is pictured in Figure 2.16.

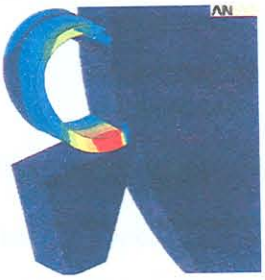


Figure 2.16: Explicit dynamic FEM model of the machining process [69]

Marty *et al.* [70] implemented a numerical simulation of machining that includes workpiece vibrations. The inclusion of vibration is very important because it has a very significant influence on the surface roughness of the machined workpiece. Lee *et al.* [71] used the FEM to determine the effect of a larger nose radius on the stress distribution in a tool insert. The areas where chipping and tool breakage will occur can be identified in this way. Marusich and Askari [72] used a numerical method to model residual stresses in machined surfaces, which is very important especially for components subject to fatigue. Very promising results were obtained.

The research works mentioned here are only a fraction of the activities in the area of FEM modelling of machining operations. In fact, Mackerle [73] presents a bibliography of FEM analysis and simulation of machining operations which covers the work from 1986-1996, and 675 research papers are included! Today, most researchers take the computational / numerical approach for research applications. Much less work is being done in the area of analytical modelling. Experimental / empirical models have the best practical application for industry. Artificial Intelligence (AI) models are also of the experimental type but are more often implemented as sensor-assisted models, and will be discussed in the next chapter. Jawahir *et al.* [74] reviewed methods for modelling turning operations at the University of Kentucky, one of most active groups in the U.S.A. The activities at the University of British Columbia are more focused on modelling of milling operations, and Altintas [75] presented an overview of their approaches. The reader is referred to these excellent overviews for more information on modelling of machining operations.

2.6 Optimisation of machining operations

2.6.1 Introduction

Tool wear studies are regularly included in manufacturing process optimisation studies. For this reason some of the basic concepts regarding machining process optimisation are discussed in this section. This will assist in comprehending some of the economic aspects with respect to tool wear. During the optimisation of most machining and manufacturing operations, the objective functions are related to economic criteria. Previous attempts to determine the optimal machining parameters can be divided into three main categories [65]:

- Computer Aided Design (CAD) approaches.
- Operations Research (OR) approaches.
- Artificial Intelligence (AI) approaches.

These approaches could be based on an off-line adjustment system, or an on-line Adaptive Control (AC) system.

2.6.2 Machining optimisation survey

The obvious optimisation problem for a turning operation will have feed and speed as variables, with the objective function linked to economic criteria. Ermer [76] developed a geometric programming technique to optimise the control variables for minimum cost, subject to constraints such as available horsepower, surface finish and available feeds and speeds. This very early work did not account for tool wear constraints. Da, Sadler and Jawahir [54] presented a computer aided methodology for predicting optimum cutting conditions in process planning of turning operations. This also involved the effect of the progressive tool wear on the performance of the machine.

Da *et al.* [54] also state that in an industrial machining process, machining performance varies due to tool wear. Empirical equations based on earlier research, were used to describe the behaviour of the different variables as well as their dependence on one another. Non-linear programming techniques were used to determine the constrained optimum cutting conditions for a certain tool wear state. Several papers are presented by the group of the University of Kentucky dealing with predictive modelling and optimisation of machining, mainly for turning operations [77-79].

Choudhury *et al.* [80] utilised an adapted version of the Taylor tool life equation (using force measurements as input) to predict the optimum cutting conditions in a turning process. This approach enabled them to predict the optimum conditions with the minimum number of experiments, given a database of the various material properties. A computer program reads the current machining conditions, determines the tool life from the Taylor equation, and then supplies the optimum parameters using a pre-established optimisation model. Zhou and Wysk [81] proposed a methodology for probabilistic optimisation in batch production, also using the Taylor equation.

Yen and Wright [40] proposed an optimisation procedure for adaptive control in machining. A safe working space is determined by the constraints of three different modes of failure. Control variables such as speed and feed rate are optimised for maximum metal removal rate. The gradual development of flank wear was also taken into account to update the optimisation dynamically. An important contribution was the establishment of a model that links the tool failure constraints with the control and state variables. Obikawa *et al.* [53] proposed a tool wear monitoring system integrated with an optimisation system for cutting conditions. The tool wear is estimated by monitoring the AR coefficients representing the power spectrum of the cutting force, and feeding it into two NNs. The machining parameters are optimised to ensure that a certain number of components can be manufactured reliably before the end of the tool life is reached. Jang and Seireg [35] proposed an optimisation procedure by which the machining parameters are optimised for specified surface conditions. Tool failure, tool wear, dimensional accuracy and chip formation are taken into account as constraints with a penalty function formulation. Maximum metal removal rate is achieved in conjunction with specified surface conditions.

2.6.3 Adaptive Control (AC)

Adaptive Control (AC) involves continuous changing in machining conditions by means of an on-line strategy, like the fuzzy-based AC system proposed by Tarng *et al.* [82]. Running an AC system based on one objective might cause an infraction on other constraints. This is why an AC system must be based on different control objectives, in order to optimise the process for the current machining conditions. Combining a range of sensors to interpret measured data can also extend the possibilities of an AC system. This is referred to as intelligent manufacturing [83,84]. The following monitoring and control functions are considered to be significant for such systems [50]:

- Advanced process monitoring, to protect from fatal events
- Adaptive Control Optimisation (ACO)
- Adaptive Control Constraint (ACC)

ACO attempts to adjust machining parameters in a direction that will optimise a predefined performance index. The aim of ACC systems is to adjust the machining parameters to their maximum possible values given the constraints of the process.

2.6.4 Approaches for Optimising Machining Operations

The conventional methods for selecting CNC machining parameters are based on textbooks or the experience of the operator. In most instances, the parameters are selected in a conservative manner in order to prevent failures such as tool breakage. As a result, the Metal Removal Rate (MRR) is low [65]. An optimisation strategy may consist of one or more of the following approaches:

A. Computer Aided Design (CAD) approaches

This off-line approach uses process, tool wear and cutting force models based on prior knowledge gathered from experiments. Based on these models, a computer simulation, using the Numerical Control (NC) code, can estimate the cutting force and tool wear. With these results, the MRR can be optimised without violating the machining constraints. The advantage of this approach is that it is easy to implement and effective for most applications. A disadvantage is the fact that the approach can only be used off-line.

B. Operations Research (OR) approaches

The objective of Operations Research (OR) approaches is to minimise global machining cost by considering multiple criteria related to machining, for example the policies developed by Jeang [85] and Akturk and Avci [86]. These methods are used for off-line adjustment due to their computational difficulty. An advantage is the establishment of a reference model that can adjust to changes in the machining parameters. Gopalakrishnan and Al-Khayyal [87] demonstrated a machine parameter selection scheme based on geometric programming for turning, which is a typical OR approach.

C. Artificial Intelligence (AI) approaches

Artificial Intelligence (AI) based methods can be used to optimise a CNC machining process. AI methods can be either ACO or ACC based, or may even be an off-line system. AI based methods attempt to automatically optimise machining parameters based on sensor information. Reaction of the control system due to changes in process must be carried out within milliseconds to ensure the reliability of the process. There have been a number of studies on the application of AI techniques in on-line control [88,89]. These can be divided into three categories:

- Neural networks
- Probabilistic inference
- Knowledge-Based Expert Systems (KBES) [90]

2.6 Conclusion

In this chapter an introduction to the mechanics of metal cutting was given. Furthermore, an overview of the turning process in general together with the main variables concerned was described. An in-depth discussion on tool wear described wear mechanisms, modes, as well as methods for wear assessment and mapping. Lastly brief discussions on modelling and optimisation techniques of machining processes were given. The amount of literature in the area of metal cutting is enormous, and the brief background reviews presented here is relevant with respect to the research that follows in the further chapters.

The recent report on "Present Situation and Future Trends in Modelling of Machining Operations" [91] reviews the many different research activities in metal cutting. Many issues connected to metal cutting have not been resolved yet. In conclusion, it could be stated that numerical methods seem to be the best way to model machining operations. However, these methods are currently of limited use in on-line TCMSs.