1.Introduction

In metal cutting as in any business undertaking, the focus lies on performing the work at hand as cost efficiently as possible. A further factor that must be kept in mind is the environmental impact that cutting fluids have. Environmental issues play an ever-increasing role in decisions affecting process development and applications of technology. Limited volume lubrication for metal cutting is able to aptly address both issues.

Very little lubricant is used and this greatly reduces the probability for skin contact by human operators, makes chip recovery easier than when conventional flood lubrication is used and decreases the possibility that the cutting fluid will tarnish the finished work-piece surface, while disposal and maintenance of used cutting fluid are not an issue. Limited volume lubrication is applied as a jet of fine mist and as a result the fine droplets have more kinetic energy than an adhered layer of conventional flood applied lubricant and thereby can displace the adhered layer on the metal surface more rapidly, providing a fresh layer of cutting fluid. Conductive and convective cooling of the cutting process are enhanced thereby.

In this study aluminium was cut using a shaper, a tungsten carbide tool and limited volume lubrication. A shaper is representative of an intermittent cutting process. All cutting process parameters were kept constant, except for the chemical composition of the cutting fluid that was used.

The aim of the investigation was to determine the effect that different cutting fluid chemistries have on intermittent cutting using limited volume lubrication as this has significant benefits to offer both in terms of cutting performance and in terms of environmental issues. The ultimate goal of the project was to develop a practical in-house test and to establish a methodology to identify and measure the parameters that should be measured in order to quantify the performance of cutting fluids used in limited volume lubrication.

To evaluate the various cutting fluids a variety of cutting process parameters were measured using a computer and relevant instrumentation. These included:

- the average tool/work-piece interface temperature, measured by means of a thermocouple that is formed by the dissimilar metals of the tool bit and the work-piece itself,
  - the temperature at which the built-up edge forms
  - the temperature at the one quarter mark of the length of cut
  - determination of the distance cut until formation of the built-up edge
- the cutting force by means of a strain gauge on the tool bit,

as well as several physical measurements of the chips formed in each cut, namely:

- the averages of the smooth distance on the underside of the chip,
- the chip thickness ratio,
- the length to first break,
- the chip shear strain,

- the shear plane angle,
- the chip hardness profile in the non built-up edge region of the cut,
- the approximate flow-zone thickness up against the rake face of the tool,
- the ease of metal deformation
- the chip shape (the chip radius in particular)
- and the surface finish on the work-piece.

When a built-up edge is not present, as is the case when higher cutting speeds are used, the welded zone should be smaller for a cutting fluid that has superior anti-weld properties and consequently the cutting force and the cutting temperature should be lower than for a cutting fluid that has lesser anti-weld properties. Better anti-weld properties should allow improved tool life and reduced operating costs as well as decrease the down-time as toolbits will have to be changed less often. At lower speeds the length that is cut prior to formation of the built-up edge in combination with the temperature at which the built-up edge forms should also give an indication of the anti-weld properties of the cutting fluid. A cutting fluid of superior anti-weld properties should show a longer smooth fraction on the underside of the chip and possibly a longer length cut to first break of the chip. If a cutting fluid is able to facilitate ease of chip flow then the chip should undergo less strain hardening despite possibly incurrring a high strain, i.e. the chip should be softer for the same amount of metal deformation than for a cutting fluid that does not facilitate ease of chip flow so well. If a cutting fluid can produce a chip that is softer than for other cutting fluids for the same cutting conditions then that cutting fluid can possibly increase the tool life. The cutting force and temperature should serve well to establish which measurements and physical characteristics of the chip produce the best reflection of the success of the cutting process.

The intent is also to use the shaper as a bench test for the evaluation of cutting fluids for metal cutting other than aluminium. To determine the success of the laboratory bench test and how well the predictions from the acquired data correlate with practice requires data from industrial applications.

It is envisaged that from research it might become possible to establish a guideline of parameters that should preferably be looked at in the laboratory for the development of cutting fluids before they are tested industrially. In the past and even now, cutting fluids are chosen and developed by trial and error. This involves a vast amount of empirical testing. The physical and chemical characteristics of lubricants and coolants may be changed and tests may be performed to determine which characteristics are desirable for a specific machining operation. Results obtained in laboratory tests sometimes do not correlate well with practice. The question is: how can laboratory tests be performed so as to achieve results that will correlate well with practice?

In this work the theoretical subject matter is divided into six parts. An overview of metal cutting is presented first. A comprehensive background is given with respect to the mechanical aspects of metal cutting, so as to provide the necessary background for meaningful interpretation of the experimental results, and for future developments. Without this background the experimental planning and interpretation of results would not be possible. Thereafter issues pertaining to the chip, such as how and where it forms and the flow patterns of the metal deformation that may be observed in the chip after it has been etched are presented. The parameters that are important to measure and how they can be measured during metal cutting are discussed next. They are cutting force and temperature. The emphasis of this study is on the cutting fluids, hence they are the parameter that changes from one test to the next and more attention is paid to the cutting fluids and their effects than to the metallurgy involved in metal cutting. The reduction of metal to metal affinity is important because this becomes manifest as anti-weld capability leading to reduced cutting temperatures and reduced tool wear when cutting with different cutting fluids. In chapter 6 the machinability of aluminium is discussed. Then the experimental apparatus and experiments conducted are described. This is followed by the results and the discussion of the results obtained, after which some conclusions and recommendations are made.

2. Metal cutting

Terminology

In order to understand the role that cutting fluids play in metal cutting an overview of metal cutting is necessary. Metal cutting cannot be performed by means of an ordinary knife. Metals and alloys are too hard, so that no known tool materials are strong enough to withstand the stresses which they impose on very fine cutting edges i.e edges that have a very fine included angle like a knife for example. If both faces forming the tool edge act to force the two newly formed surfaces apart very high stresses are imposed, much heat is generated, and both the tool and the work surfaces are damaged. These considerations make it necessary for a metal-cutting tool to take the form of a large-angled wedge, which is driven asymmetrically into the work material, to remove a thin layer from a thicker body. (See figure 2.1)

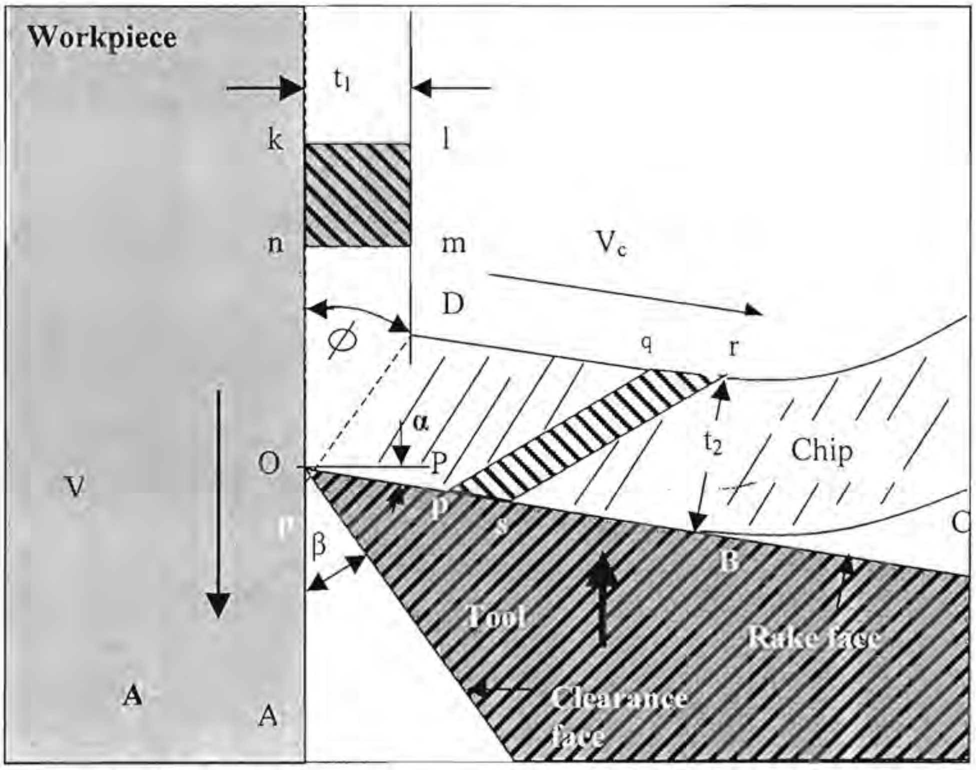

Figure 2.1 Metal cutting diagram for the tool and the work-piece (Trent,1977)

The layer must be thin to enable the tool and the work to withstand the imposed stress. There exists a range of how thin the tool can be to still have sufficient rigidity and mechanical strength to withstand the imposed stress and how thick without causing extreme chip deformation, work hardening and increased operating costs. A clearance angle β must be formed on the tool to ensure that the clearance face does not make contact with the newly formed work surface, because this will lead to increased friction and undesired surface defects like scratches. If the heat build up in this region becomes too intense a tertiary welded or contact zone will develop leading to more shear and yet more heat and rapid catastrophic tool failure may result due to overheating. These are features of all metal cutting operations and provide common ground from which to commence an analysis of machining.

In figure 2.1 the angle α between the rake face and the line OP is called the rake angle. The chip must flow over the rake face. The cutting edge is formed by the intersection of the clearance face, or flank, with the rake face. The rake angle is measured relative to the line OP and if the rake face lies below this line it is referred to as a positive rake angle. The rake face is inclined at an angle to the axis of the work material and this angle can be adjusted to achieve optimum performance for a particular tool material, work material and cutting conditions. This refers to the rake angle.

Positive rake angles (α) may be up to 30° but the greater robustness of tools with smaller rake angles leads in many cases to the use of zero or negative rake angle. (See figure 2.2)

Metal Cutting Operations and Terminology

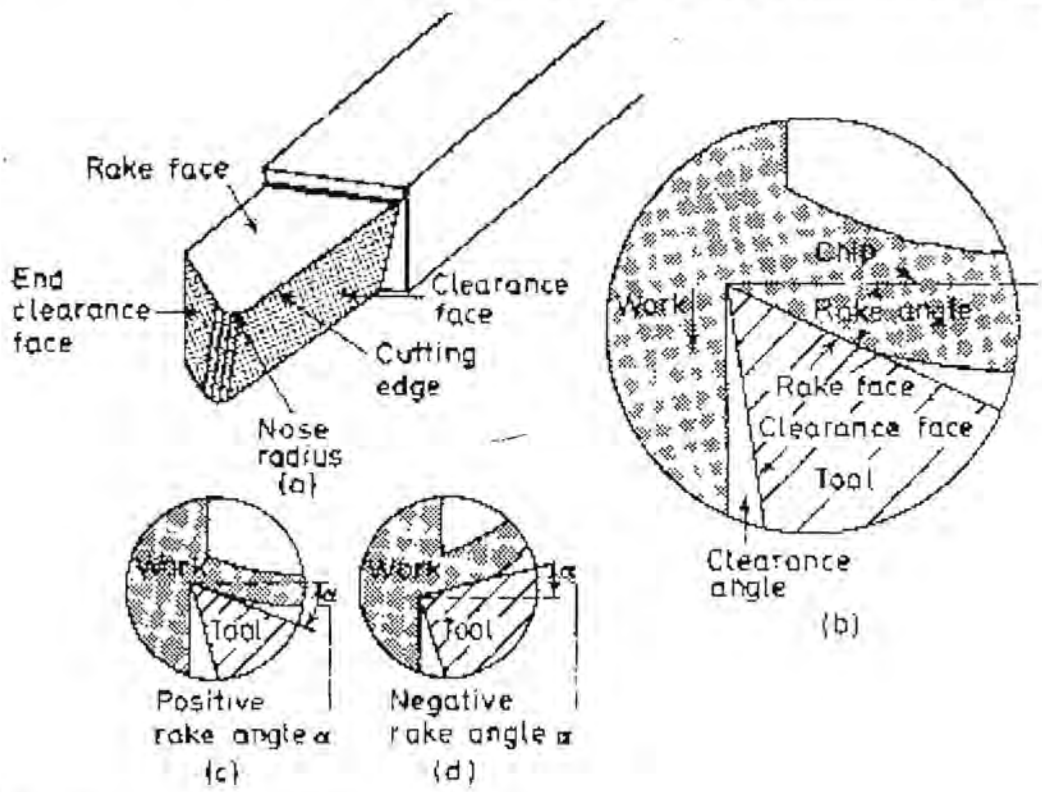

Figure 2.2 Cutting tool terminology.
(Trent, 1977)

The tool terminates in an end clearance face (see figure 2.2(a)) which also is inclined at an angle as to avoid rubbing against the freshly cut surface. The nose of the tool is at the intersection of all three faces and may be sharp, but more frequently there is a nose radius between the two clearance faces.

For the shaper that was used in this study the tool looks somewhat different (see figure 2.3).
The different parameters that play a role in metal cutting, are (Boston, 1952)

- the material of construction of the cutting tool
- the hardness of the cutting tool
- the red hardness or hot hardness of the cutting tool
- the temperature at which the tool operates
- the depth of cut
- the feedrate of the workpiece

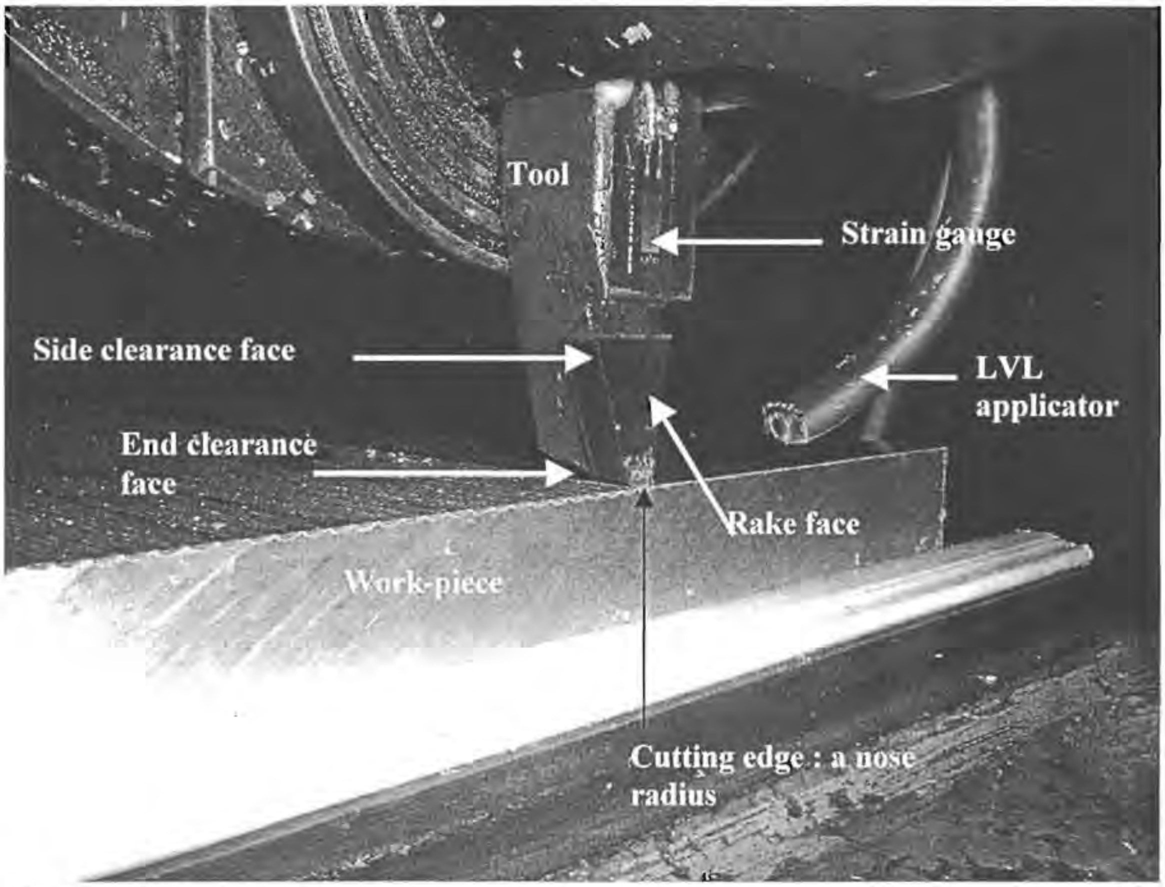

Figure 2.3 View of the tungsten carbide cutting tool in the shaper

- the cutting speed
- the volumetric rate of metal removal
- the structure of the metal being cut
- the stiffness of the metal being cut
- the toughness of the metal being cut
- the hardness of the metal being cut
- the toughness of the tool and the shank material
- the stiffness of the tool and the shank material
- the hardness of the tool material

- the heat capacity and the conductivity of the tool material
- the treatment of the tool during preparation of the tool. The treatment can involve peening and different heat treatments.
- the geometry of the cutting tool, and that includes a keen cutting edge. Hand ground tools will never have the same geometry from one time of sharpening to the next. This would result in non-repeatability of results during testing
- the cutting fluid used and its properties (to be discussed later)
- the atmosphere in which the metal cutting occurs. (Bartz, 1996)
- the type of machine used for the cutting process

According to de Chiffre and Belluco (de Chiffre & Belluco, 2002) the performance ranking of cutting fluids is not independent of the type of machine tool used, nor is it independent of the type of work material that is used. The hypothesis was investigated that one will get the same performance ranking for the different metal working fluids that were used regardless of which machining test is used, when the fluids are of the same type. For water-based fluids they used on austenitic stainless steel the hypothesis was mostly true, but the ranking did change depending on the test for the straight oils. This difference was even more pronounced for other work materials. Esters and vegetable oils performed best in all the tests in both the water-based and the straight oil group. The tests that were used were turning, drilling, reaming and tapping.

The type of machine that is used can be one for continuous cutting or one for intermittent cutting. With continuous cutting a steady state temperature is attainable provided that no built-up edge is present. With intermittent cutting the temperature at the tool tip continuously fluctuates. If this fluctuation becomes excessive, large thermal stresses are imposed on the tool tip that can contribute to comb crack formation which may lead to accelerated tool wear.

In machining cutting fluid may be considered an accessory that is frequently applied in order to increase production rate, improve surface quality, reduce costs and consequently increase profit. This is true in most applications but it can also cause problems in a few cases. Machining with ceramic tools, particularly alumina-based ceramics, with inadequate fracture toughness, may not tolerate the application of cutting fluid. The heated zone in the tool promoted by the cutting action will experience thermal shocks in the presence of cutting fluid which often leads to severe cracks or even fracture of the entire tool edge.
Cutting fluid can also be detrimental to intermittent cutting operation, such as milling, where comb cracking is the major tool failure mode. This failure mode can be enhanced by fluctuation of the cutting temperature, heating in the active period of cut and cooling in the idle period during revolution of the milling cutter. This temperature fluctuation causes stress variation on the tool due to a steep temperature gradient, leading to the formation of cracks usually perpendicular to the cutting edge, and culminating in the formation of comb cracks. Application of cutting fluid under this situation will further increase the temperature fluctuation due to its cooling ability during the idle period, thus increasing the stress variation and consequently accelerating the process of comb crack formation. (Vieira, Machado and Ezugwu, 2001)

Depth of cut is always measured in the direction in which there is no motion. The feed direction and the cutting direction both experience motion.

It is difficult to appreciate the action of many types of tool without actually observing or, preferably using them. **The performance of cutting tools is very dependent on their precise shape.** In most cases there are critical features or dimensions which must be accurately formed for efficient cutting. These may be the clearance angles, the nose radius and its blending into the faces, or the sharpness of the cutting edge. The importance of precision in tool making, whether in the tool room of the user, or in the factory of the toolmaker, cannot be over-emphasised.

Most of the practical work that was performed for this investigation was done on a shaper. (See figure 2.4) Shaping is one of the methods that can be used to produce flat surfaces, grooves or slots. In shaping, the tool has a reciprocating movement; the cutting takes place on the forward stroke along the full length of the surface that is generated. On the return stroke the cutting tool has to be lifted clear so as to prevent wear on the tool and damage to the work surface. The next stroke happens once the work-piece has moved on laterally horizontally or vertically by the set feed distance. The cutting times between interruptions are longer than in milling operations but shorter than in most turning operations.

A shaper was used rather than a saw blade or a saw tooth as a saw tooth would lack sufficient mechanical rigidity if it would protrude far enough from the tool holder so that a strain gauge can be mounted on its surface. The strain gauge is necessary for cutting force data collection. Also the geometry of a saw tooth would need to be adapted so that for a long open chip, the chip would not end up damaging the strain gauge due to clogging up the gullet. The gullet is the space between two consecutive saw blade teeth. The blade would also only be equipped with one strain gauge, as strain gauges on the following teeth of the blade would run a higher risk of becoming damaged. Multiple strain gauges would not necessarily result in more useful data capture for cutting fluid evaluation. A shaper can also produce grooves, as can a saw, thus operating the shaper in this way results in performing the same task and consequently the data that is captured should also be quite relevant for a sawing operation.

The shaper has a clapper box and this has a pivot (see figure 2.4). On the push stroke when the tool is cutting, the tool is held down into the cut. On the return stroke the tool pivots up and slides over the work-piece, so that the tool does not cut on the return stroke. The depth of cut is how deep the tool goes into the metal, and is determined by adjusting the position of the vertical slide.

The cutting tool that was used for the experimental work on the shaper is a tungsten carbide tool (see figure 2.3). In practical machining with a shaper the included angle of the tool rake face and the plane of machining varies between 60° and slightly more than 90°, so that the removed layer, the chip, is diverted through an angle of at least 60° as it moves away from the work, across the rake face of the tool. In this process, **the whole volume of metal is subjected to plastic deformation** and thus a large amount of energy

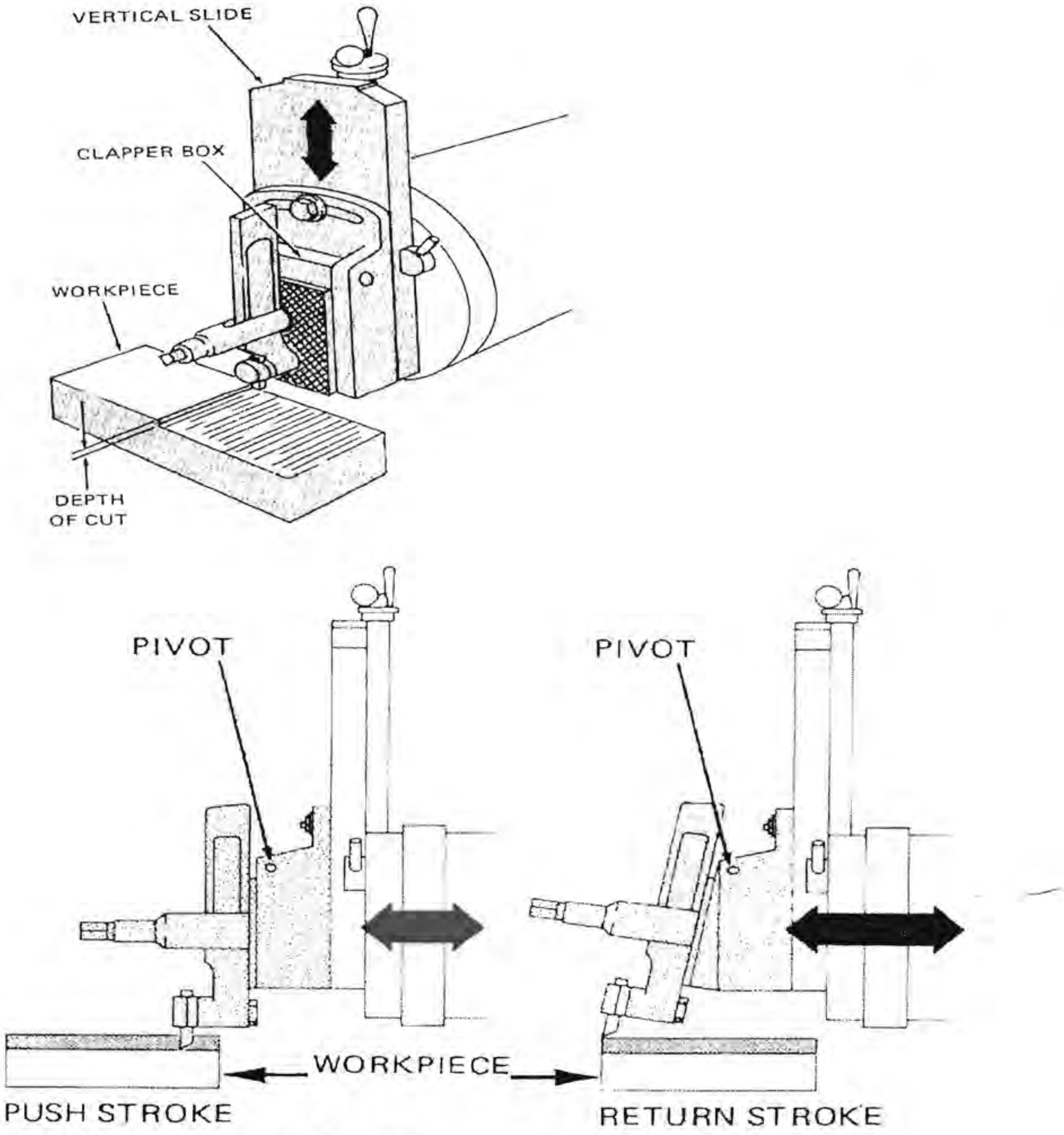

Figure 2.4 Schematic of a shaper
(Follette D.,1980)

is required to form the chip and to move it across the tool face. In the process, two new surfaces are formed, the new surface of the work-piece (OA in figure 2.1) and the under surface of the chip (BC). To form new surfaces requires energy, but in metal cutting this represents an insignificant amount of the energy for cutting as most energy goes into plastic deformation of the whole volume of metal when forming the chip. (Trent, 1977). The cutting force measurement by strain gauge includes only the force necessary to perform the cut and thus does not incorporate the force that the electric motor must provide to drive the machine tool. Similarly, the energy for cutting does not include the energy needed to drive the machine tool.

That a large amount of energy is required to form the chip may be substantiated in another way. If one looks at a chip under a scanning electron microscope (SEM) (see figure 2.5) a large number of slip bands are evident on the rough chip surface. If each slip band is taken as a new surface that was produced then the total area of the surfaces produced in the chip far exceeds that of the surfaces at the underside of the chip and on the work-piece surface.

If one further takes into account that these surfaces are sheared across each other under conditions of seizure and/or high friction and that the chip is being moved and deformed to curl as it leaves the tool, then it is clear that most of the energy during cutting goes into forming the chip.

The main objective with machining is forming or shaping the work surface to the desired geometry. Based on this it may appear that most of the attention should be paid to the forming of new surfaces, but the main energy consumption takes place in the forming and

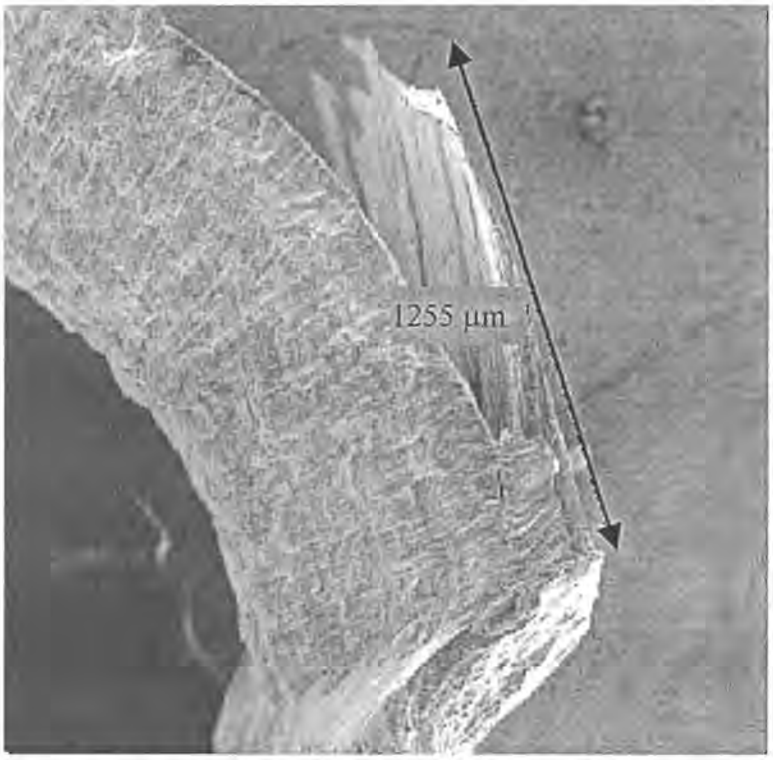

Figure 2.5 Part of a chip under a SEM at 2500X magnification

moving of the chip, therefore the main economic and practical problems concerned with rate of metal removal and tool performance, can be understood only by studying the work material as it is formed into the chip and moves over the tool. Even the condition of the machined surface itself can be understood only with knowledge of the process of chip formation.

The rate of metal removal may be determined by the following relationship:

$$R = v \cdot w \cdot t_1 \qquad \textbf{Eqn 2.1}$$

where
R is the rate of metal removal (cm^3/min)
v is the cutting speed (m/min)
w is the width of the cut and (mm)
t_1 is the depth of cut (mm)
The cutting speed and the feed rate or amount fed per cut are the two most important parameters which can be adjusted by the operator to achieve optimum cutting conditions.

The chip

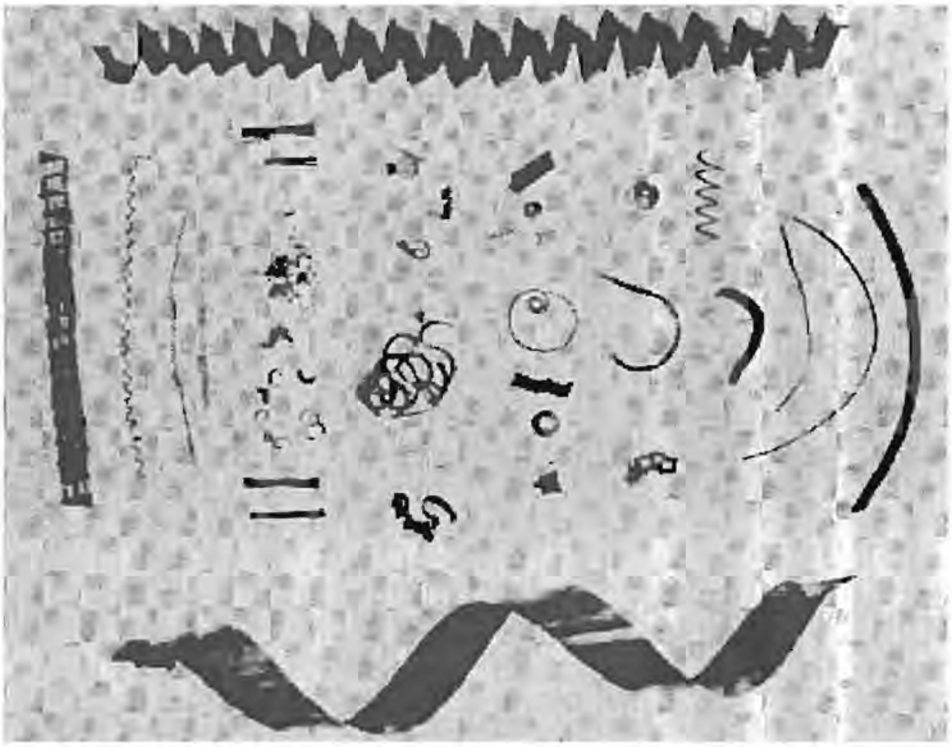

Figure 2.6 Chip shape an essential feature of metal cutting.

The chip is enormously variable in shape and size in industrial machining. Figure 2.6 shows some of the forms. The formation of all types of chips involves shearing of the work material in the region of a plane extending from the tool cutting edge to the position where the upper surface of the chip leaves the work surface (OD in figure 2.1). A very large amount of strain develops in this region in a very short time, and not all metals and alloys can withstand this strain without fracture. Grey cast iron chips, for example, are always fragmented, and the chips of more ductile materials may be produced as segments under unfavourable conditions of cutting. This discontinuous chip is one of the principal classes of chip form, and has the practical advantage that it is easily cleared from the cutting area. Under a majority of cutting conditions, however, ductile metals and alloys do not fracture on the shear plane and a continuous chip is produced. Continuous chips may adopt many shapes – straight, tangled or different types of helix shapes. Often they have considerable strength, and controlling size and chip shape is one of the problems machinists and tool designers face.

Simple chips, i.e. those chips that have only two dimensions, are the easiest to measure and analyse. Chip shape depends on the tool geometry, the lubricant and the mode of lubrication that is used and on other parameters like the type of metal being cut, the feed rate, the cutting speed and the type of tool that is used. Continuous and discontinuous chips are not two sharply defined categories, and a transition between the two types can be observed.
The longitudinal shape of continuous chips can be modified by mechanical means, for example by grooves in the tool rake face, which curl the chip into a helix. **The longitudinal cross-section of the chips and their shape and thickness are of great importance in the analysis of metal cutting,** and need to be considered in some detail. For the purpose of analysing the cutting process chip formation in relation to basic principles of metal cutting should be studied. It is useful to start with the simplest cutting conditions, consistent with maintaining the essential features common to cutting operations. (Trent, 1977)

Techniques for the study of chip formation:

Firstly the conditions are simplified for the beginning stages of a laboratory investigation. These conditions are known as orthogonal cutting. In orthogonal cutting the tool edge is straight, it is normal to the direction of cutting, and also normal to the feed direction. In this study a shaper is used and this meets the requirements of orthogonal cutting. The cutting speed is the same at each point on the cutting tool. Depending on the cut and the tool that is used, the chip is free to move to both sides, or to one side, or to no side at all but only to the top. When a chip can move to no side at all, but to the top, it will be referred to as bi-directional restraint of chip flow. These chips are two-dimensional. The cutting is intermittent, as is also the case with a sawing operation and a milling operation.

The time of continuous machining on a shaper is short and speeds are limited. There are eight different speeds available on the shaper used for this study, and they range from about 5.7m/min to 90m./min. The study of the formation of chips is difficult because of the speed of the cutting operation in industrial machining and because of the small scale of the phenomena that are to be observed. The shaper in this case is better than a lathe because it meets orthogonal cutting conditions more closely than a lathe since on a lathe the cutting speed can change significantly from one point on the tool to another when a small radius work-piece is machined and the depth of cut is deep. Another reason for using the shaper is that it offers single cut motion, the cut is simple i.e. with bi-directional restraint of chip flow the cut is symmetrical and the feed force is balanced from either side which gives a resultant force of zero. The downward force is negligibly small in relation to the cutting force and the feed force (Trent, 1977, and Follette D, 1980) and therefore force analysis is the simplest possible for the metal cutting operation as it becomes one dimensional for all practical purposes. (See also figure 2.4 and figure 3.1).

In the past high-speed cine-photography at low magnification was used to reveal the changing external shape of the chip (Trent, 1977). Today this kind of work is done by means of a high speed digital video camera. A thousand frames per second or more are possible. Such a camera can be a very useful accessory. "The external shape can be misleading if used to reflect the cutting action at the centre of the chip." (Trent,1977) The outermost layer of the chip is much cooler than the innermost layer. This and that the external shape can be misleading is quite obvious when one studies the internal chip deformation from lateral cross sections after etching and from studying micro-hardness profiles through the chip.

No useful information about chip formation can be gained by studying the end of the cutting path after cutting has been stopped in the normal way by disengaging the feed and the drive to the work. (Trent, 1977). By stopping the cutting action suddenly, however, it is possible to retain many of the important details – to 'freeze' the action of cutting.

Chip shape:

Even with orthogonal cutting the chip shape is not strictly rectangular. For the case of performing the cutting operation with a shaper the chip is free to move as mentioned above. The chip flows in all the directions in which it is not constrained.

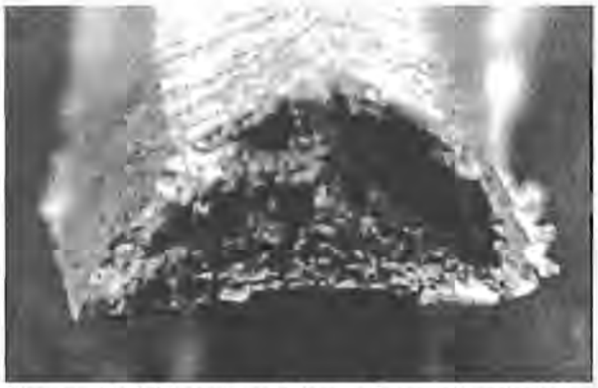

Figure 2.7 Cross section of an aluminium chip showing thick middle section and taper towards sides

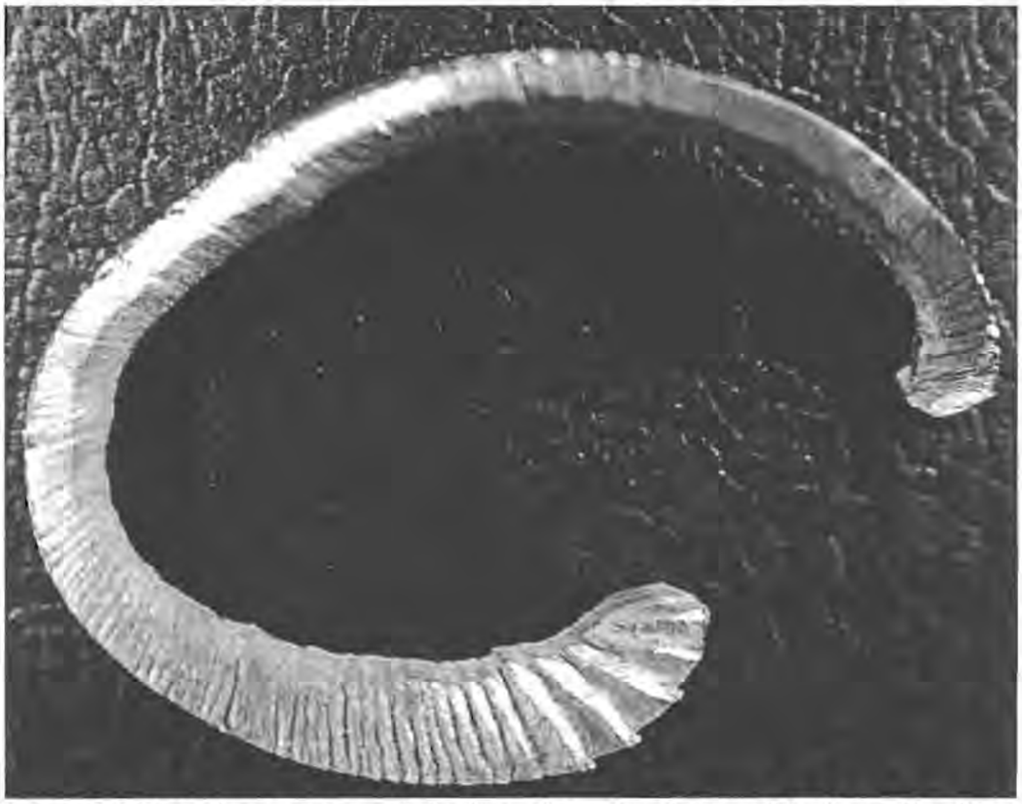

Figure 2.8 Rough upper serrated edge of an aluminium chip from the shaper

The chip spread is smaller with harder alloys, but when a softer metal is cut using a small rake angle, chip spread of more than one and a half times the original depth of cut has been observed (Trent, 1977). Usually the chip is the thickest in the middle, tapering off somewhat towards the sides (see figure 2.7), but this depends on the constraints of the available volume into which it can flow.

The upper side of the chip is always rough, usually with minute corrugations or steps as is clear from figure 2.8. It is interesting, especially from figure 2.7, that the chip cross section is not perfectly round, but actually is a five sided shape. The reason for this probably is that the metal exposes its surfaces of lowest surface energy for maximum stability. (See appendix A) Compare this with the shape of the tool of figure 2.3 - the tool has a round cutting edge as it has a nose radius.

Even with a strong continuous chip periodic cracks are often seen, breaking up the outer edge into a series of segments. A complete description of chip form would be very complex, but, for purposes of analysis of stress and strain in cutting, many details can be ignored and a much-simplified model may be assumed. The making of these assumptions is justified in order to build up a valuable framework of theory, provided it is kept in mind that reality can be completely accounted for only by reintroducing the complexities, which were ignored in the first analysis.

An important simplification is to ignore both the irregular cross section of real chips and the chip spread, and to assume a rectangular cross section, whose width is the measured mean width of the chip, and whose height is the measured mean thickness of the chip. With these assumptions, the formation of chips is considered in terms of the simplified diagram, figure 2.1, an idealised section normal to the cutting edge of a tool used in orthogonal cutting.

Chip formation

In practice, the mean chip thickness can be obtained by weighing the chip and measuring the length of a piece of chip. The mean chip thickness, t_2, is then

$$t_2 = 1000 \cdot M / \rho \, w \, l \qquad \text{Eqn. 2.2}$$

where t_2 = mean chip thickness (mm)
M = mass of the chip (g)
ρ = the density of the work material/chip material (assumed to be the same) (g/cm^3)
w = the width of the chip (mm)
and l = length of the piece of chip (mm)

The mean chip thickness is a most important parameter. In practice the chip is never thinner than the feed, which in orthogonal cutting, is equal to the undeformed chip thickness, t_1, (figure 2.1). Chip thickness is not constrained by the tooling, and, with many ductile metals, the chip may be as much as five times as thick as the feed, or even more.

The chip thickness ratio is defined as t_2 / t_1. The chip thickness ratio may also be obtained in another way, namely by marking the work piece with permanent marking ink at a known distance from the beginning of the cut. When the cut is completed, the chip is collected and the distance from the start of the chip to where the mark appears on the chip is measured. The ratio of the first length to the second length is the mean chip thickness ratio.
The chip thickness ratio t_2 / t_1 is geometrically related to the tool rake angle and the shear plane angle ϕ (figure 2.1), as will be shown below. (Trent, 1977).

The shear plane angle is the angle formed between the direction of movement of the work-piece OA (figure 2.1) and the shear plane represented by line OD, from the tool edge to the position where the chip leaves the work surface. For purposes of simple analysis the chip is assumed to form by shear along the shear plane. In fact the shearing action takes place in a zone close to this plane. The shear plane angle is determined from experimental values of t_1 and t_2 using the relationship

$$\cot \Phi = (t_2/t_1 - \sin \alpha)/\cos \alpha \qquad \text{Eqn. 2.3}$$

And, where the rake angle, α, is zero

$$\cot \Phi = t_2/t_1$$

The chip moves away with a velocity v_c which is related to the cutting speed v and the chip thickness ratio

$$v_c = v \cdot t_1 / t_2 \qquad \text{Eqn. 2.4}$$

If the chip thickness ratio is high, the shear plane angle is small and the chip moves away slowly, while a large shear plane angle means a thin, high velocity chip.
As any volume of metal, e.g. *klmn* figure 2.1 passes through the shear zone, it is plastically deformed to a new shape *–pqrs*. The amount of plastic deformation (shear strain γ) has been shown to be related to the shear plane angle ϕ and the rake angle α by the equation (Hill, 1950)

$$\gamma \;=\; \cos\alpha \,/ (\sin\Phi \cdot \cos(\Phi - \alpha)) \qquad \text{Eqn. 2.5}$$

See figure 2.9 for a graphical representation of strain vs. shear plane angle. The longer the contact-zone or welded zone the hotter is the flow-zone and consequently also the thicker. The metal is softer and thus deforms more easily and a higher chip strain and a smaller shear plane angle are observed. When the cutting speed is increased the welded-zone becomes smaller and the heat affected region although hotter is smaller and less strain in the chips is observed.

As the force analysis is really simple for cutting on a shaper and the cutting speed is kept constant in the experiments that were done the work done vs. strain attained by the chips would be an interesting quantity to display graphically. For the shaper the work is given by the sum of the work on the shear plane and on the rake face.

$$d/dt(W_r(t)) = Q_r(t) = F_c(t) \cdot v_c \qquad \text{Eqn. 2.6}$$

Where W_r is the work performed on the rake face (J)
t is time (s)
Q_r is the rate at which work is done (Watts)
F_c is the cutting force (N) and
v_c as previously is the chip velocity (m/s).

After integration it follows that

$$W_r(t) = \int F_c(t) \cdot v_c \; dt \qquad \text{Eqn. 2.7}$$

All necessary data is available for numerical integration from the experiments that were performed.

The work (W_s) done on the shear plane is given by

$$d/dt(W_s(t)) = F_s \cdot v_s \qquad \text{Eqn. 2.8}$$

Where F_s is the shear force and v_s is the strain rate on the shear plane.

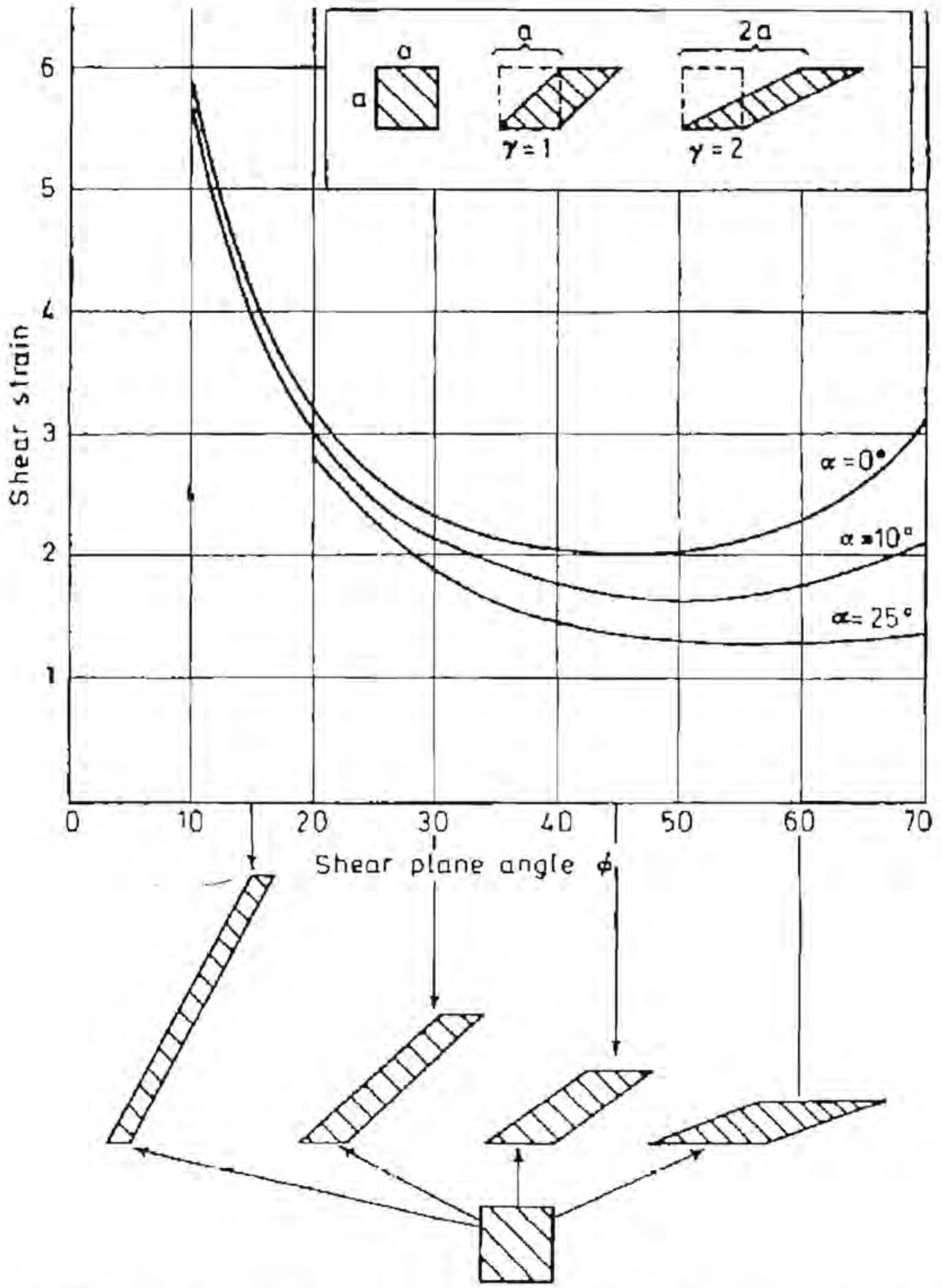

Figure 2.9 Strain on shear plane (γ) vs. shear angle (φ) for three values of rake angle (α) (Trent, 1977)

The shear force is given by

$$F_s = F_c \cdot cos\, \Phi - F_f \cdot sin\, \Phi \qquad \text{Eqn. 2.9}$$

(Trent,1977).

Since the Feed force F_f on the shaper is zero, the second term of equation 2.9 falls away. The strain rate on the shear plane is given by

$$v_s = v \,/\, cos\, \Phi \qquad \text{Eqn. 2.10}$$

and can easily be determined from figure 2.1 and work on the shear plane is thus:

$$W_s\,(t) = \int F_c\,(t) \cdot v\; dt \qquad \text{Eqn 2.11}$$

The total amount of work done in the cutting process is equal to the sum of the work done on the rake face and on the shear plane.

The graph of figure 2.9 shows the relationship between the shear strain in cutting and the shear plane angle for three values of the rake angle. For any rake angle there is a minimum strain when the mean chip thickness is equal to the feed ($t_2 = t_1$). For zero rake angle the minimum is at $\phi = 45°$. The change of shape of a unit cube after passing through the shear plane for different values of the shear plane angle is shown in the lower diagram of figure 2.9 for a tool with a zero rake angle. The minimum strain of the cube is apparent from the shape change. It is obvious that the more knife-like the cutting tool becomes i.e. the larger the rake angle becomes the less the chip is strained.

At zero rake angle the minimum shear strain is 2. Strain has units of length per length and therefore is dimensionless. The minimum strain becomes less as the rake angle is increased, and if the rake angle could be made very large; strain in the chip formation could become very small. In practice the optimum rake angle is determined by experience. Too large a rake angle weakens the tool and leads to fracture. Rake angles of greater than 30° are seldom used. In practice the tendency is towards a small rake angle because this way the tool can be made more robust. Harder but less tough tool materials can be used. Even under the best cutting conditions there is severe plastic deformation of the chip as it forms and this results in work hardening and structural change. It is not surprising that metals and alloys that lack ductility are sometimes fractured on the shear plane.

The Chip/Tool interface

The formation of the chip by the shearing action at the shear plane has attracted most of the attention in analyses of machining. It is equally important for the understanding of machinability and the performance of cutting tools to pay attention to the movement of the chip and of the work material across the faces and around the edges of the cutting tool. In most analyses this has been treated as a classical friction situation, in which 'friction forces' tend to restrain movement across the tool surface, and the forces have been considered in terms of a friction coefficient (μ) between the tool and the work materials. Detailed studies of the tool/work interface have shown that **this approach is**

inappropriate to most metal cutting conditions (Trent, 1977). Classical friction concepts do not apply.

According to classical friction principles the coefficient of friction (μ) is dependent only on (F) the force required to initiate sliding or to maintain sliding, and the normal force (N) at the interface at which sliding is taking place. The friction coefficient is defined as the ratio of the force(F) to the normal force (N). Put another way, the shear force (F) is proportional to the normal force (N). The friction coefficient is thus independent of the sliding area of the two surfaces. The proportionality results from the fact that real solid surfaces are never completely flat on a molecular scale, and therefore make contact only at the peaks of the asperites, while the valleys on the surfaces are separated by gaps. A profilometer can be used for measurement of the profiles of surfaces.

The frictional force is that force required to separate or shear apart the areas in actual contact at the asperity peaks. Under normal loading conditions for sliding, this real contact area is very small, often less than 0.1% of the apparent area of contact of the sliding surfaces. When the force acting normal to the surface is increased, the area of contact at the tops of the hills is increased in proportion to the load. The frictional force required to shear the contact areas, therefore also increases proportionately, so that the sliding force is directly proportional to the normal force. The above concepts are thus adequate for many engineering situations where stresses between the surfaces are small compared to the yield stress of the materials.

When the normal force is increased to such an extent that the real area of contact is a large proportion of the apparent contact area, it is no longer possible for the real contact area to increase proportionately to the load. In the extreme case, as with metal cutting, the two surfaces are in complete contact with each other and the real area of contact becomes independent of the normal force. Remember that in metal cutting due to metal shearing and friction there is enough heat build-up so that a welded-zone forms. (See also Hutchings 1992, but it must be pointed out that the load there is a static load and in metal cutting the load is dynamic, i.e. the load in metal cutting is applied where the two surfaces are in relative motion.) The force required to move one surface over the other becomes that necessary to shear or continue to shear the weaker of the two materials across the whole area. This force is almost independent of the normal force, but directly proportional to the apparent area of contact – a relationship that is directly opposed to that of classical friction concepts. This is evident for example when a built-up edge forms on the rake face of the tool or when a restricted contact tool is used then the apparent area of contact decreases and the cutting force decreases correspondingly. (see also figure 3.2)

It is therefore important to know what conditions exist at the interface between the tool and the work material during cutting. This is a very difficult region to investigate. Few significant observations can be made while cutting is in progress, and the conditions existing must be inferred from studies of the interface after cutting has stopped, and from measurements of stress, hardness profiles and temperature. The conclusions are deduced from studies mainly made by electron and optical microscopy (Trent, 1977), of the interface between work material and tool after use in a **wide** variety of cutting conditions.

Evidence comes from worn tools, quick-stop sections and from chips. In this study aluminium was cut and because it is soft relative to steel no worn tool resulted and the only evidence that was gathered came from measurements of cutting force and temperature during cutting and from the chips themselves.

The most important conclusion from the observations is that contact between tool and work surfaces is so nearly complete over a large part of the total area of the interface due to metal to metal welding, that sliding at the interface is impossible under most cutting conditions. (Trent,1977)

The evidence from optical electron microscopy demonstrates that the surfaces investigated (Trent,1977) are interlocked or seized to such a degree that sliding, as normally happens between surfaces with only the high spots in contact, is impossible. Some degree of metallurgical bonding is suggested by the frequently observed persistence of contact through all the stages of grinding, lapping and polishing of sections. There is however a considerable variation in the strength of bond generated, depending on the tool and the work materials and the cutting conditions.

In some cases the separation of the work material from the cutting tool occurs at the interface between the tool and the work material, but in other cases the break occurs in the chip itself. The chip undergoes ductile tensile fracture close to the interface, but not at the interface. This observation is from looking at cross-sections from quick-stop experiments. In quick-stop experiments the tool is explosively propelled away from the cutting position during cutting. (Trent,1977)

In the aluminium cutting that was done the separation occurred at the interface between the tool and the work-piece.

This kind of evidence demonstrates the mechanically interlocked and/or metallurgically bonded character of the tool-work interface as a normal feature of metal cutting. Under these conditions of cutting **movement of metal cannot be adequately described by the terms friction and sliding.**

They are inappropriate for two reasons:
- 1) there can be no relationship between the forces normal and parallel to the tool surface and
- 2) the force parallel to the tool surface is not independent of the total area of contact, but on the contrary, the area of contact between the tool and the work material is a very important parameter in metal cutting.

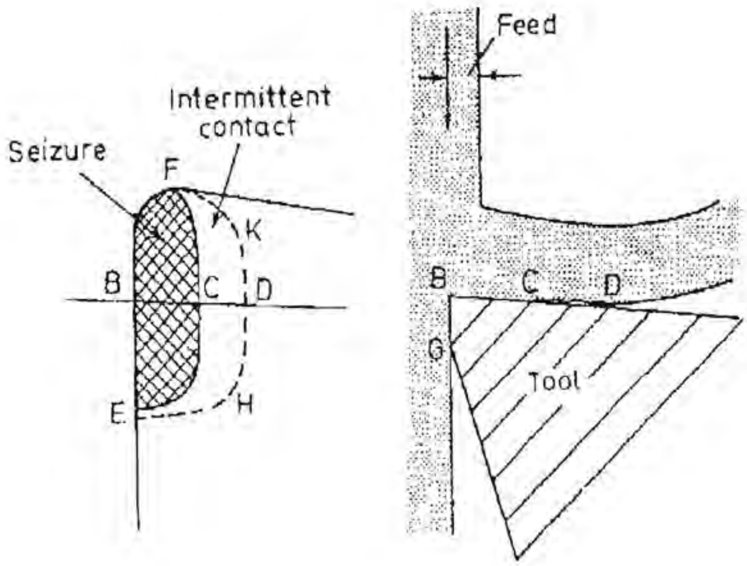

Figure 2.10 Areas of seizure on cutting tool

(Trent, 1977)

The size of this contact area or welded area directly influences the cutting forces and temperature. If it is bigger, metal is sheared for longer and a larger flow-zone, and consequently higher cutting forces and higher cutting temperatures are seen. The conditions at the work/tool interface are referred to as conditions of seizure as opposed to conditions of sliding. (Trent, 1977).

There is an enormous variety of cutting conditions that are encountered in practice. Mostly cutting takes place under conditions of seizure, but there are some situations where sliding does occur. This happens at very low cutting speeds of only a few cm/min and at these cutting speeds sliding is promoted by active lubricants. Low cutting speeds are common at the centre of a drill. Even under normal conditions of seizure it must be rare for the whole of the area of contact to be seized together. (figure 2.10)

The flank also undergoes wear. The flank is the underside of the cutting tool where the rake angle and the clearance angle apexes meet. BG represents the worn flank region and this counts as a secondary contact-zone in which more heat is generated and once the zone becomes large enough as flank wear progresses the tool overheats and tool failure is inevitable.

Chip Flow under conditions of seizure

Under sliding conditions relative movement of the surfaces can be considered to take place at the interface between the two bodies. Under seizure conditions this is not the case, because the force required to overcome the interlocking and bonding is normally higher than that required to shear the weaker of the two materials. The weaker material is thus sheared in a region of finite thickness which may lie adjacent to the interface or at some distance from it, depending on the stress system involved.

In sections through chips and in quick-stop sections, zones of intense shear near the interface are normally observed (see figure 2.11), except under conditions of sliding. This observation will partly be used for evaluation of cutting conditions on the experimental shaper set-up.

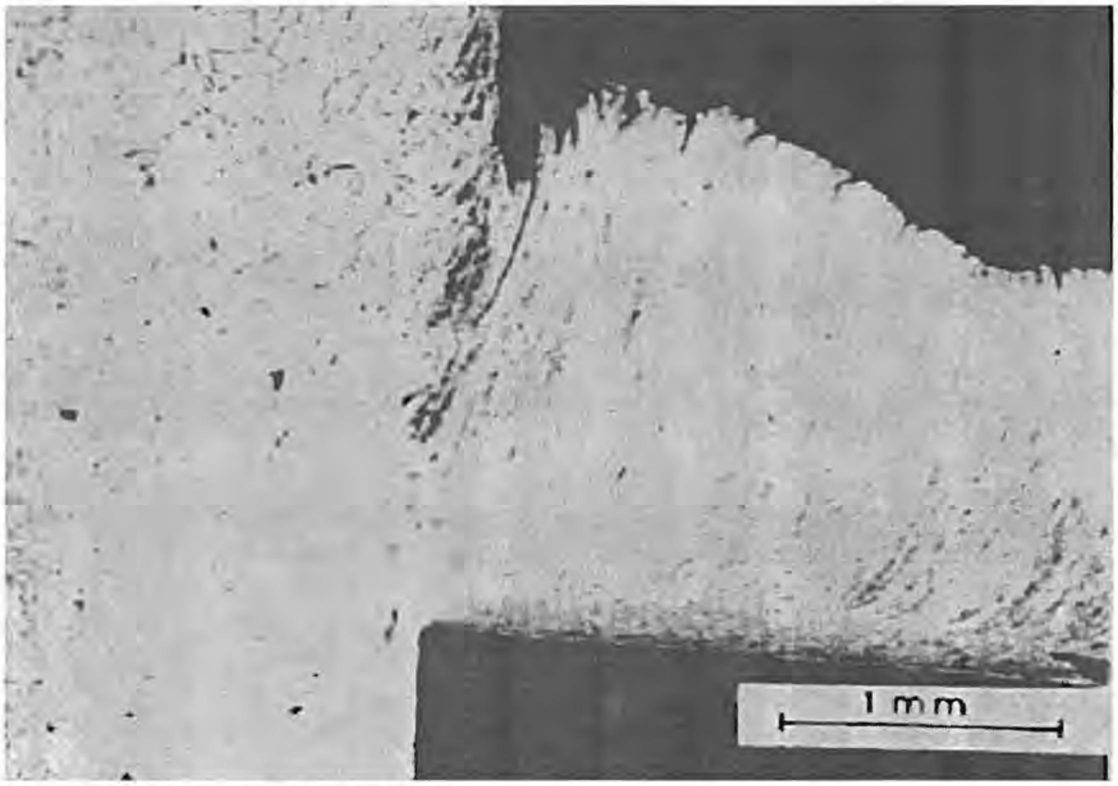

Figure 2.11 Section through quick-stop showing flow-zone against the rake face

(Trent, 1977)

The thickness of these zones is often of the order of 25 to 50 μm and strain/deformation within these regions is much more severe than on the shear plane, so that normal structural features of the metal or alloy being cut can be greatly altered or completely transformed. **It is in this region that the maximum temperature in the cutting process must be encountered.** The behaviour of the work material in these regions is in many ways like that of a very viscous liquid rather than that of a normal solid metal. Hence this region is referred to as the flow-zone. **The flow-zone blends in gradually with the rest**

of the chip meaning that there is no clear-cut distinction between the flow-zone and the chip or the work-piece. There is a flow pattern seen as a metal deformation pattern in the work material around the cutting edge and across the tool faces in the chip. The thickness and the pattern of the flow-zone is characteristic of the metal being cut and of the conditions during cutting. Different cutting fluids also affect the thickness of the flow-zone. The amount of strain and the degree of work hardening in the chip can vary greatly, depending on the material being cut, the tool geometry, and the cutting conditions, including whether a lubricant is used or not, and if a lubricant is used : the type of lubricant that is used. This is intended to be one of the focus areas of this study: i.e.:

i) what can and does the lubricant do for metal cutting and
ii) how can the chemistry involved contribute positively to the cutting process

The built-up edge (BUE)

The built-up edge is a condition of seizure that gives rise to one of the major types of chip formation. When cutting metal, hardened work material adheres around the cutting edge and along the rake face. It accumulates to displace the chip from immediate direct contact with the tool as shown in figure 2.12.

The built-up edge occurs frequently in industrial cutting and can be formed with either a continuous or a discontinuous chip as is the case with cutting steel and cast iron respectively.

The built up edge is not a separate body of metal during the cutting operation. It can be depicted as shown in figure 2.13 as the region that is shaded with a grey metal grain texture. It is welded to the tool surface. The maximum heat region is now somewhat removed from the tool surface as the flow-zone is in the chip very close to the interface between the built-up edge and the chip.

The built-up edge is between A and B and is continuous with the work material and the tool because there is seizure between the work material and the tool. The flow zone has been moved to the top of the built-up edge and is no longer on the tool surface. The new work surface is forming at A and the under surface of the chip is forming at B. The built-up edge is dynamic and is constructed of successive layers which are greatly hardened under extreme strain conditions. The size of the built-up edge cannot increase indefinitely. There comes a point when the shear stresses increase so much that part of the built-up edge is sheared off and carried away on the work surface or on the underside of the chip. In some cases the stress on the built-up edge becomes such that the whole build-up is sheared from the tool surface. After that the formation of a new built-up edge starts. The built-up edge is undesirable, because if it is sheared off and passes on the underside of the tool, it causes surface defects such as tears, smears and deposits on the worked material and it contributes to tool wear.

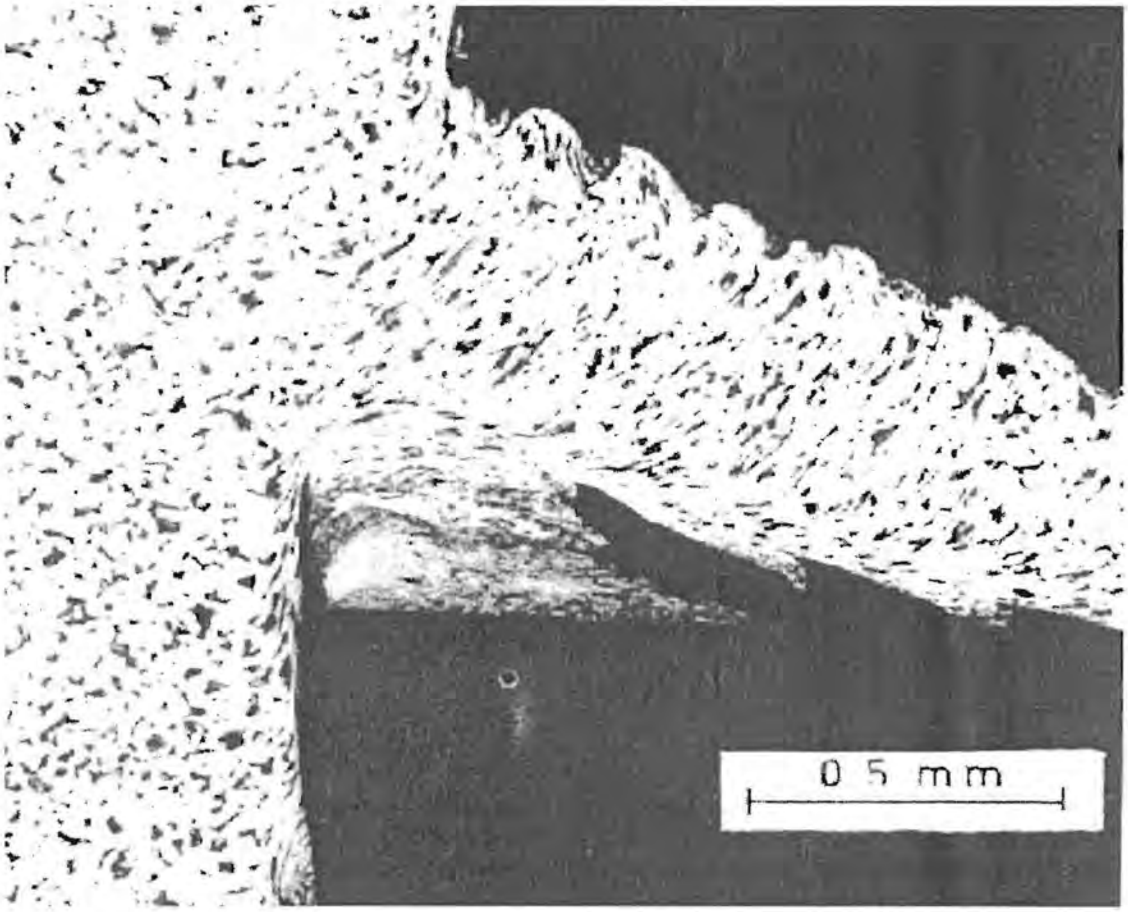

Figure 2.12 Section through quick-stop showing built-up-edge
(Trent, 1977)

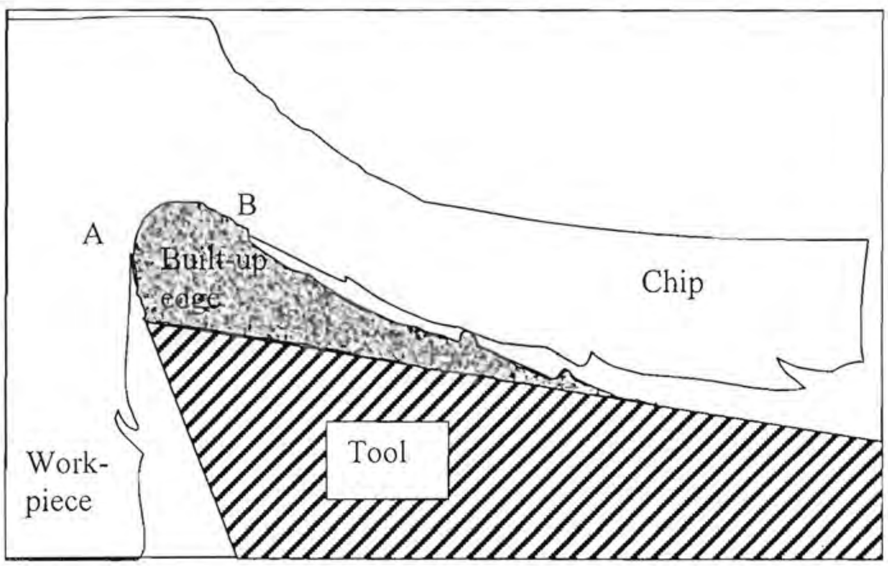

Figure 2.13 Shape of the built-up edge

(Trent, 1977; Follette, 1980)

There is no hard and fast line between the built-up edge and the flow zone. Compare figures 2.11 and 2.12. Seizure between tool and work material is a feature of both a built-up edge and a flow-zone and every shade of transitional form between the two can be observed. The built-up edge occurs in many shapes and sizes and it is not always possible to be certain whether it is present or not.

The built-up edge that is sometimes produced during metal cutting can be a major factor in influencing tool wear. At low cutting speeds, the built-up edge is more prevalent. A built-up edge can reduce tool life in one of at least three different ways. Firstly, when the built-up edge breaks away, it may take small fragments of the cutting edge with it. Secondly, the surface behind the built-up edge can experience severe wear in the form of a groove. Finally, since the tool material and the built-up edge material have different coefficients of thermal expansion, the heating - cooling cycle can produce cracks in the tool surface causing "flakes" of material to be removed. (Bartz, 1992)

The machined surface for analysis of the cutting process

Figures 2.11 and 2.12 demonstrated that the machined surfaces are formed by a process of fracture under shearing stresses. With ductile materials, both sides of a shear fracture are plastically strained, so that some degree of plastic strain is a feature of machined surfaces. The amount of strain and the depth below the machined surface to which it extends, can vary greatly , depending on the material being cut, the tool geometry, and the cutting conditions, including whether a lubricant is being used or not, and if a lubricant is used; the type of lubricant that is used.

The deformed layer on the cut surface can be seen as part of the flow pattern around the cutting edge which passes off with the work material, so that an understanding of the flow-pattern, and the factors which control it, is important in relation to the character of the machined surface. The presence or absence of seizure on those parts of the tool surface where the new work surface is generated can have a profound influence on the cutting process, as can the presence or absence of a built-up edge and whether the tool that is used is sharp or worn. The properties of the machined surface that are influenced are:

- the plastic deformation
- the hardness
- the roughness
- the precise geometry and
- the appearance.

3. Monitoring of the Cutting Process:

3.1 Parameters of the cutting process

A further factor to bear in mind when studying the cutting process is the cutting force. It is noted in the experimental work done that cutting forces are usually abnormally low when a built-up edge is present and that it is a phenomenon that occurs between two phased alloys but not with pure metals. The same was found by Trent. (Trent, 1977. The built-up edge changes the cutting conditions and therefore it should be avoided. The built-up edge acts like a restricted contact tool, effectively reducing the length of contact on the rake face (See figure 2.12). The cutting force is also lower for alloys than for pure metals over the whole cutting speed range, but is more pronouncedly so at low speeds than at high speeds. The reason for this is that alloys have a eutectic composition, that has a lower melting point than either of its constituent metals. (Rollason, 1973). That this is more pronouncedly so at low speeds is due to the melting of the pure metals being less complete as the cutting temperature in the flow-zone is lower. It is common experience, when cutting most metals and alloys, that the chip becomes thinner and the cutting force decreases when the cutting speed is increased. This is partly caused by a decrease in contact area and partly by a drop in shear strength in the flow zone as the temperature rises with increasing speed.

Tool speed or cutting speed is critical for tool life. The relationship between cutting speed and tool life may be plotted on a log-log graph from data and using the Taylor Equation (Follette, 1980; Trent, 1977; and Boston 1952) The Taylor equation in its simplest form is given by

$$v \cdot T^{n} = C \qquad \text{Eqn 3.1}$$

Where v is the cutting speed (m/min)

T is the tool life (min.)

C is a constant and is equal to the cutting speed on the log-log plot for a tool life of one minute. It is dependent on the conditions, the tool, the material, and the cutting fluid that is used.

n is the slope of the straight line on the log-log plot.

Tool life is also affected by fatigue. Mechanical fatigue, also caused by snap loading, and thermal fatigue are noteworthy contributors to tool failure, particularly in operations of an interrupted nature such as milling and shaping. The thermal fatigue is caused by the constant heating and cooling cycle in interrupted cutting. If the temperature difference between the hottest and coldest part of the cycle is too extreme minute cracks in the form of comb cracks start to develop in the tool surface.

Monitoring cutting force during metal cutting is also useful for determination of the state of wear of the tooling. Tools wear in several ways. In flank wear the flank below the side cutting edge is partly worn away by rubbing against the work-piece. The wedge of metal that is worn away leaves a land and the width of this land can be used to measure flank wear. In each case where a land forms, the area in the plane where shear occurs is increased. The force needed to shear the work material on this plane is equal to the shear strength of the work material multiplied by the shear area, hence when this area increases the cutting force increases too, and by monitoring the cutting force it may be determined how far wear has progressed.

There is a minimum energy theory for the cutting of metals. The energy needed to do a cut is the work done on the shear plane and varies with the shear plane angle, and this curve therefore has the same shape as the curve for a tool with zero rake angle with a minimum at a shear plane angle of 45°. For a zero rake angle tool the minimum strain or metal deformation during cutting happens at a shear plane angle of 45°, (see figure 2.9). It is thus logical to have expected this because least deformation for a particular rake angle should correspond to least energy needed to perform the cut. (Trent, 1977).

The performance of tool dynamometers was greatly improved with the introduction of wire strain gauges, transducers or piezo-electric crystals as sensors to measure deflection to be able to calculate the cutting forces.

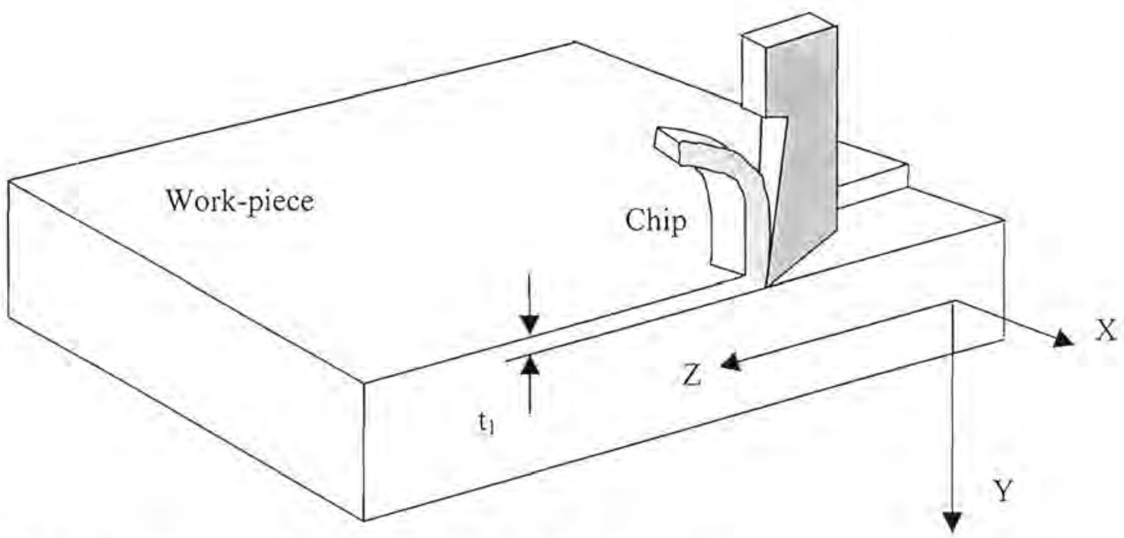

Figure 3.1 Schematic of the cutting process on the shaper

The cutting force F_c, is in the direction of the cut. That is in the Z direction on figure 3.1. It is usually the largest of the three force components and is referred to as the cutting force. The other force component is the feed force F_f and it acts in the direction parallel to the feed i.e., in the X-direction on figure 3.1. Lastly the normal force F_n, normal to the work-piece surface, that tries to push the tool out of the work-piece acting along the longitudinal axis of the tool, i.e. in the Y-direction on figure 3.1, is the smallest of all the components and is usually ignored and not even measured. It is referred to as the longitudinal force. t_1 indicates the depth of cut.

At low values of ϕ for the shear plane angle, the chip is thick, the area of the shear plane becomes larger, and, therefore the cutting force, F_c becomes larger. Therefore the

consequence of increasing either the shear yield strength at the rake face, or the contact area (length) is to raise the cutting force F_c.
As feed on the shaper takes place between cuts the feed force does not influence the cutting process, thus it is not monitored. The lateral force that would be classified as the feed force is balanced out in the experiments that were done as bi-directional restriction on chip flow was used. The contact area on the tool rake face in particular is seen to be a most important region, controlling the mechanics of cutting, and is a point of focus for research in metal cutting.

Pure metals are notoriously difficult to machine. The reason being that the cutting forces are high because the contact area on the rake face is very large and the shear plane angle is small and the very thick strong chips move away at slow speed.

The large contact area is probably associated with the high ductility of these pure metals. (Trent, 1977). One explanation for this is that the pure metals have a more regular crystal lattice structure with no interference from foreign metals or not the same metal atoms and that their atoms therefore can slide over each other more readily and therefore stay in contact with the cutting tool for longer. That the forces are due to the large contact area can be demonstrated by using a tool of restricted contact area as shown in figure 3.2.

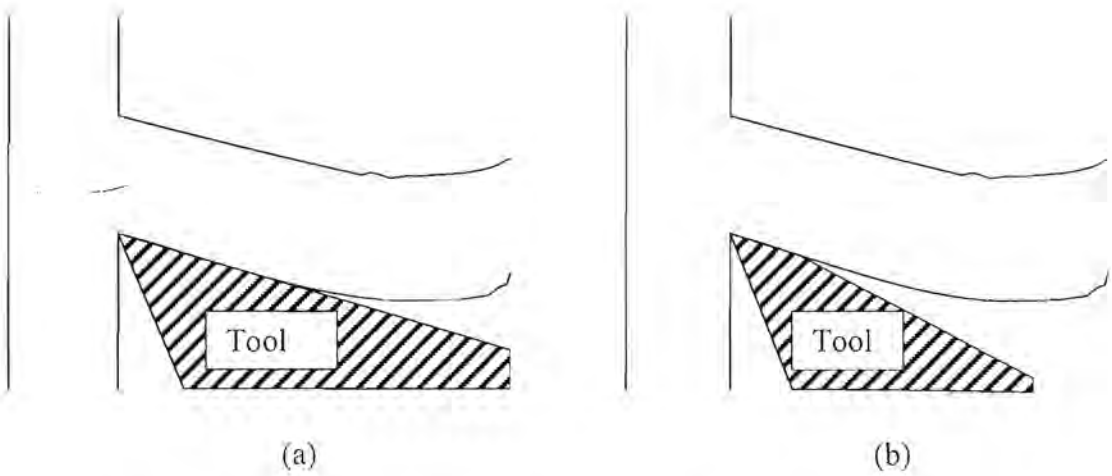

Figure 3.2 (a) Normal Tool; (b) tool with restricted contact on rake face

Results reported by Trent (Trent, 1977) show that the tool forces are much smaller (about half of those for the normal tool) for the tool of restricted contact. One possibility for experimental determination of contact lengths is to use tools of various restricted contact lengths and to see at which length the cutting force starts to decrease.

Reduction of the cutting forces by restricting the contact area on the rake face may be a useful technique in some conditions, but in many cases it is not practical because it weakens the tool. When the contact areas are small the chips that are produced are thin.

This then is another useful indication for a change in contact area. When only the cutting fluid and no other cutting parameter is changed and this observation is made then the contact area on the cutting tool may be determined from an etched micrograph and compared for the different cutting fluids. This would indicate that a cutting fluid has the ability to decrease the metal to metal affinity of the tool and the work-piece material.

It is common experience that when the cutting speed is increased when cutting most metals and alloys, that the tool forces decrease and the chips become thinner, but the temperature profile in the tool becomes higher i.e. the localised hot spots become hotter.

The decrease in tool forces is attributable to the decrease in shear strength in the flow-zone of the work material as it becomes hotter and also to the decrease in contact area upon increases in temperature, up to a point, thereafter upon further increases in temperature welding is promoted the contact area increases and when this becomes too intense the tool will fail catastrophically.

3.2 Heat in Metal cutting

The power consumed in cutting metal is mainly converted into heat in the flow-zone near the cutting edge of the tool, and many economic and technical problems are caused directly or indirectly by this heating action. The rate of metal removal that is attainable plays an important role in the economy of the cutting operation. There is however a limit to the rate, as too fast a metal removal rate will result in the tool life being shortened excessively. This is because the temperature of the tool at the contact-zone becomes too hot resulting in a decrease in its hardness and a corresponding increase in tool wear. When machining the softer metals and alloys tool life may not be the constraint, but rather the ability to handle large quantities of fast moving swarf.

It is important to understand the factors, which influence the generation of heat, the flow of heat and the temperature distribution in the tool and the work material near the tool edge. Determination of the temperatures and the temperature distribution in the vitally important region near the cutting edge is technically difficult. This region has fast dynamics, is very small and the conditions are harsh. To fit sensor equipment for temperature data acquisition in this region is not presently possible. Only methods such as micro-hardness tests and temperature dependent metal structure formations from which temperature and temperature distribution may roughly be inferred are used.

For an investigation into the chemistry of the lubricants used for the cutting process these temperatures also play a role because they influence the activation energy available for chemical reactions to occur.

Under most cutting conditions, the largest part of the work is done in forming the chip at the shear plane. In a simple model of action on the shear plane, the work material is heated instantaneously as it is sheared and all the heat is carried away by the chip. By this model, the temperature of the chip increases according to equation 3.2. (Trent, 1977).

$$T_C = n \cdot k \cdot \gamma / (J \cdot \rho \cdot C) \qquad \text{Eqn. 3.2}$$

where T_c = temperature increase in chip body (°C)
k = shear flow stress (N/m^2)
γ = shear strain dimensionless
J = mechanical equivalent of heat (kJ)
ρ = density (kg/m^3)
C = heat capacity (kJ/kg.°C)
n = constant (J)

A different equation to calculate chip temperature is given by Zorev & Shaw, 1966.This equation is very tedious to use and falls outside the scope of this investigation.

A reasonable estimate of the temperature that is reached within the chip body can be made in this way particularly at relatively high cutting speeds. The temperature of the chip can only affect the performance of the tool as long as it is in contact with the tool. After the chip breaks contact with the tool, the heat remains in the chip and is carried away with it out of the system. After the chip has become hot upon passing through the shear-zone it is not further deformed and heated as it passes over the rake face, and the time to pass over the rake face is very short. A cutting speed of 60 m/min. and a chip thickness ratio of two would give a chip speed of 30 m/min. For a contact length of 1mm on the rake face this equates to a time of 2 milliseconds as 30m/min is 500mm/s. This is a very short time and very little heat can be lost from the chip by any heat transfer mechanism. This is only based on the model and for this model the flow-zone has been ignored.

In reality heat may also be lost from the chip to the tool via conduction through the contact-zone or welded zone. This is so for very low cutting speeds. For speeds where the flow-zone just above the welded zone forms, the temperature in the flow-zone is higher than in the rest of the chip body. Heat then tends to flow into the chip body from underneath and no heat is lost from the chip into the tool by conduction. The chip temperature increases only very little because the flow-zone is very thin. Heat is also lost from the flow-zone into the tool.

The heat that is transferred to the work-piece from the shear plane can be partially accumulated in chips when more than one cut on or near the same place on the surface is made. For this reason the work-piece is often cooled so as to ensure dimensional accuracy. Part of the shear zone on the shear plane passes under the tool cutting edge and this leaves behind on the worked surface a heated and strained or deformed layer that has a very variable thickness. Any factors that contribute to a small shear plane angle increase the heat flow into the work-piece and the ductility of the work-piece. Alloying and any treatments to reduce the ductility of the work material or a larger shear plane angle, usually reduce the residual strain in the work-piece surface.

The heat generated at the tool/chip interface is of major importance in relation to tool performance. A reasonably good estimate of the amount of heat generated at the tool/chip interface can be made from the force and the chip thickness measurements. For a zero rake angle tool the heat generated, Q, is

$$Q = F_c \cdot v_c \qquad \text{Eqn.3.3}$$

Where F_c is the cutting force (N)
v_c is the chip velocity (m/s)

The temperature of the chip can be calculated with considerable accuracy, equation 3.2, because there is little error involved in assuming even distribution of strain rate across the shear plane, and neglecting heat losses during the short time interval involved. This simplification cannot be made for calculating temperatures in the flow-zone for three reasons:

1. Energy distribution in the flow-zone may be very non-uniform and the data from which to calculate it are unreliable because of the extremes of strain, strain-rate etc.
2. The thickness of the flow-zone, and the amounts of metal passing through are not accurately known.
3. The heat losses from the flow-zone may be large and difficult to calculate.

Many attempts have been made to calculate temperatures and temperature gradients on the rake face of the tool. The accuracy of these calculations is subject to considerable doubt. Although quantitative estimates of temperature by calculation are uncertain, it is helpful in understanding many aspects of tool life and machinability, to consider the general character of the flow-zone as a heat source. The material in the flow-zone is changing continuously since new material is continuously fed into the zone and it is sheared, deformed and compressed along all the way until it leaves the flow-zone.

Shearing and deformation heats the material significantly, and the temperature increase depends on the amount of work done on the quantity of metal passing through the flow-zone. The thickness of the flow-zone provides some measure of the latter; and the thinner the flow-zone the higher the temperature would be for the same amount of work done. The thickness varies considerably with the material being cut from more than 100 μm to less than 12 μm. It tends to be thicker at low speeds, but does not vary greatly with the feed. In general the flow-zone is very thin compared with the body of the chip – commonly of the order of 5% of the chip thickness. Since the work done at the tool rake face is frequently about 20% of the work done on the shear plane, much higher temperatures are found in the flow-zone than in the chip body, particularly at high cutting speeds.

The temperature in the flow-zone is also strongly influenced by heat loss by conduction because the heat is generated in a very thin layer of metal which has a large area of metallic contact both with the body of the chip and with the tool, i.e the area to volume ratio for this layer is very large. The maximum temperature in the flow-zone is way back from the cutting edge and is reduced by heat loss by conduction into the chip. (see figure 3.3) After the chip leaves the tool surface, that part of the flow-zone which passes off on the under surface of the chip, cools very rapidly to the temperature of the chip body, because cooling by metallic conduction is very efficient. The increase in temperature of the chip is slight because of the relatively large volume of the chip body.

The conditions of heat loss from the flow-zone into the tool are different from those at the flow-zone/chip body interface because heat flows continuously into the same small volume of tool material. The bond at this interface is often completely metallic in character, and when this is true, as it often is, then the tool will effectively have the same temperature as the flow-zone material at the surface of contact. Under constant operating conditions a stable temperature gradient is built up in the tool as it acts as a heat sink into which heat flows from the flow-zone. The amount of heat lost from the flow-zone into the tool depends on the thermal conductivity of the tool, the tool shape, and any cooling method used to lower its temperature. The heat flowing into the tool from the flow-zone raises its temperature and this is the most important factor limiting the rate of metal removal when cutting the higher melting point metals.

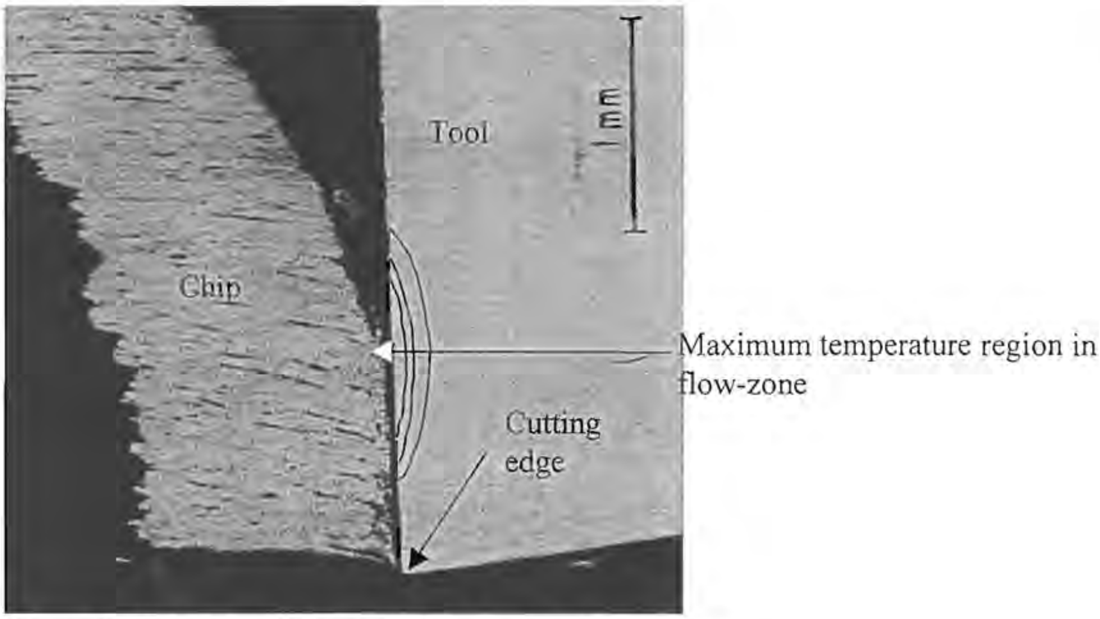

Figure 3.3 Maximum temperature region in flow-zone

(Adapted from Trent, 1977)

With aluminium and the other softer lower melting point materials the problem is to cope with large quantities of fast moving swarf. Managing chip shape here is therefore an important parameter. The temperatures reached in the flow-zone however do affect the surrounding material like the tool, the chip and the kind of lubricant, if used, and therefore for purposes of measuring lubricant performance in the cutting process it is important to be able to determine the temperatures and temperature profiles in response to the various lubricants used for metal cutting. The type of material used for the tool and the type of material that constitutes the work-piece and the temperatures that are reached can all affect the chemistry of the lubricant that is used.

The tool clearance face needs to have a large enough clearance angle to prevent it from rubbing against the newly formed surface on the work material. A reasonable clearance angle is typically between 5° and 10 °. Making the clearance angle too big weakens the tool too much. With using a smaller clearance angle, 1° for example, there is a risk that a long contact path on the clearance face is established and this will be a third heat source, similar in character to the flow-zone on the rake face. Even with normal clearance angles, prolonged cutting results in 'flank wear', in which a new surface is generated on the tool more or less parallel to the cutting direction. A 'wear land' develops and the work material is often seized to it and when the wear land becomes long enough it becomes a serious heat source. Generation of high temperatures in this region is usually followed by immediate collapse of the tool.

3.3 Methods of tool temperature measurement

It is difficult to calculate temperatures and temperature gradients at or near the cutting edge, even for very simple cutting conditions. This indicates that it is important to be able to measure the temperatures, hence a few of the experimental methods used are now discussed.

Tool-work thermocouple

The tool/work-piece thermocouple method of tool temperature measurement makes use of the tool and the work material as the two elements of the thermocouple. The thermo-electric e.m.f. that is generated between the two dissimilar metals is typically of the order of millivolts. With standard thermocouples a 1°C-temperature change results in a few tens of microvolts change in the e.m.f. that is generated at the hot junction. The hot junction is the contact area at the cutting edge, while an electrical connection to a cold part of the tool forms the cold junction. The tool is electrically insulated from the machine tool; i.e. it is electrically floating. For the case of this investigation the machine tool is a shaper. Cutting is thus constant and intermittent. Care must be taken to avoid secondary electrical connections such as can happen when using tipped tools or when the chip curls back onto the tool as when using a chip breaker.

The e.m.f. can be measured and recorded during cutting. To convert the microvolt signal that is recorded to temperature it is necessary to calibrate the tool/work thermocouple against a standard thermocouple. Each different combination of tool and work material used must be calibrated separately.

This method of temperature determination is not so easy as it seems; it is subject to several sources of error. Somehow these errors must be eliminated or compensated for. Firstly the tool/work thermocouple does not consist of ideal thermocouple materials consequently the e.m.f. that is generated is low and the e.m.f. temperature response is far from linear. One may need to amplify the measured signal several hundred times for use as a signal into a computer for data logging. With the amplification can be associated a significant amount of noise and this can cause difficulty in interpreting the observed signal. If the signal is not amplified and only measured and recorded with a sensitive millivoltmeter there may be noise that is camouflaged in the signal and thus one may not be aware of its presence. It is further doubtful that the thermo-e.m.f from a stationary couple, used in calibration, corresponds exactly to the thermo-e.m.f. during cutting conditions where the work material is severely strained. When calibration is done the conditions are static and during cutting, the conditions are dynamic. An experiment will show the effect that straining the tool/work-piece interface has on the e.m.f. that is generated.

Quite a large number of test results have been reported by other workers for different tool and work materials. (Trent, 1977; and Boston, 1952) All investigations show a large increase in temperature as the cutting speed is increased. The temperatures reached are dependent on the amount of material that passes through the flow-zone per time unit, i.e. on the amount of material being sheared per time unit. The dimensions of the flow-zone change with cutting speed. Temperatures of over 1000°C have been recorded. The reliability of the measured temperatures is in doubt because of the very steep gradients that exist at the tool/work interface. Figure 4.3 shows that these gradients are very steep. Under these conditions the measured e.m.f. may represent a mean or average value for the temperature, or possibly the lowest temperature at the interface. The use of thermocouples in the sub-surface of the rake face have the same problem, and they are further away from the flow-zone than the tool/chip interface is.

Another way of eliminating errors is to electrically insulate the aluminium work-piece in ceramic and then heat the work-piece. An RTD (resistance temperature device) is inserted into a hole very close to the tool/work-piece junction and the work piece is heated with a gas torch. As aluminium is a good conductor of heat, the RTD and the tool work-piece junction will be very close to the same temperature. Using a computer to log the temperature data corresponding to the e.m.f. as the work-piece is heated makes it possible to set up an nth order polynomial that relates the e.m.f. to temperature directly. (Considine, 1974; and Capgo, 2002).

Inserted thermocouples

To measure temperature and distribution of temperature in the tool has been the objective of many experimental studies. (Trent, 1977; Varadarajan, Philip & Ramamoorthy, 2001; and Kelly & Cotterell, 2001)
One simple but tedious method is to make a hole in the tool in the region where the temperature is to be measured, and to insert a thermocouple in a precisely determined place close to the cutting edge. For determining temperature distribution this process needs to be repeated many times in holes at different places so that temperature mapping can be done. The problem with this is twofold: 1) the tool is weakened by drilling the hole into it and 2) the temperature gradient in the tool is very steep. It is of the order of 300°C/mm and higher per positional change. (See figure 4.3) Now a thermocouple tip is

more than 1 mm in diameter, so the question is where exactly is it measuring the temperature? It is clear that this method will not be satisfactory to determine temperature distribution.
This method is probably as satisfactory in comparing tool temperatures when cutting different alloys as the tool/work thermocouple.

Other methods

Other methods involve:

i) measuring the radiation from the heated tool areas, but used to have the drawback that they only give an indication of the temperatures on the exposed surfaces. Nowadays remote sensors like single wavelength, dual wavelength and multi wavelength devices, which are non-contact devices, have special forms of filtration so that that they can read below the surface of a molten metal. (Brown, 2002) The problem however still remains one of exactly how deep below the surface and over what size of area is the measurement taken. Temperature gradients in metal cutting are extremely steep, as will be shown in chapter 4.

ii) An infra red laser type thermometer can also be used. This bounces an infrared ray on the surface where the temperature is to be measured, but also has the drawback that it can only measure the temperature on the exposed surfaces.

iii) The exposed surfaces can be photographed using film that is sensitive to infrared radiation. The heat image of the tool and the chip on the film is scanned using a micro-photometer, and from the intensity of the image the temperature gradient on the exposed surface may be plotted. For the rake surface the maximum temperature occurs at some distance back from the cutting edge, and the temperature is lower near the cutting edge itself.

iv) Yet another method is to use a PbS photo-resistor. By using tools with small holes in different positions and focussing the heat image through these holes onto the PbS photo-resistor, which is calibrated to measure temperature, a map of the temperature distribution on the rake face may be constructed. (Trent, 1977)

Structural changes in high speed steel (HSS) tools

The temperature gradients in three dimensions throughout the part of the tool near the cutting edge, are estimated by observing the structural changes in the metal of high speed steel tools under cutting conditions where the temperature is raised over 600 °C. This temperature and temperatures well in excess are reached when machining the high melting point metals and alloys at relatively high cutting speeds. Above 600°C HSS's are rapidly 'over-tempered' – the hardness after heating decreases and the structures pass through a series of changes which can be followed by micro-examination after polishing and etching. Polished sections are etched in Nital (a 2% solution of HNO_3 in alcohol) to reveal structural changes. The changes in tool steel can be followed by means of micro-hardness tests. There is a rapid decrease in hardness in those parts, which have been heated between 650 °C and 850 °C, and an increase in regions heated to temperatures above the transformation point, i.e. 900°C where the structure becomes austenitic and re-hardens when it cools very rapidly.

The above could come in useful for the performance evaluation of coolants and lubricants in as much that it could possibly help to verify the length of the contact/welded zone as the heat affected region should be smaller for a cutting fluid that is able to reduce the metal to metal affinity and able to enhance the Rebinder effect (Hutchings, 1992). The Rebinder effect is a chemo-mechanical effect that includes environmental factors that can influence plastic flow, by affecting the mobility of near-surface dislocations. Surface chemical reactions are greatly enhanced by friction. The Rebinder effect may be detected from micro-hardness measurements, (Hutchings, 1992) The softer the metal the more ductile/bendable it is. If the chip can thus curl easier then it will experience less work hardening and if it can curl sooner then a shorter welded-zone should result, which should result in cooler operating conditions or at least a smaller heat affected region.