5.Metal to metal affinity

The structure of metals:

Metals have a metal lattice structure and are arranged in unit cells. Depending on the unit cell they can have a bulk co-ordination number of 8 or 12 i.e. they have 8 or 12 nearest neighbours. The fcc (face centred cubic) unit cell structure for example has a bulk co-ordination number of 12 The nearest neighbours are those atoms that are in direct contact with an atom in the bulk of the metal lattice structure. Miller indices refer to planes of symmetry through the metal lattice structure. Depending on the Miller index i.e. the plane on which the lattice is cut the co-ordination number of the surface atoms changes. Only the simplest of planes are usually considered when studying metal surfaces. (See Appendix A) Surface atoms have different co-ordination numbers than atoms in the bulk of the metal lattice. The atoms from the cutting fluids must locate on or between the surface atoms and their co-ordination number and how firmly they are attached to the metal surface depends on how they locate and attach to the metal surface.

The nature of the metallic bond:

The metal atoms in the metal lattice are bonded to each other by means of de-localised electrons. The electrons are shared between the atoms but not only between two atoms, as is the case in covalent bonds but between the nearest neighbour atoms. The metallic bond consists of a "sea" of electrons that is composed of the de-localised electrons. Depending on the atomic orbital of the atoms in the lattice there are more or less electrons that can be de-localised, and depending on the size of the atoms i.e. how many protons they have there is more attractive or less attractive force available to keep the electrons close to the atomic nucleus. The bulk co-ordination of atoms in the metal lattice can also contribute to the amount of de-localised electrons in the electron "sea" around the atoms in the metal lattice. This is why the strength of the metallic bond varies. Generally the denser the cloud or sea of electrons in the lattice the stronger the metallic bond, and the higher the melting point and boiling point of the metal will be. This is why many of the transition metal elements have a high melting point. The metallic bond is only really broken once the metal boils. When the metal melts the atoms are still loosely associated as the ordered structure has broken down, but the metallic bond is still present, hence boiling point is actually a better indication of bond strength for a metal than melting point. (Clark, 2002)

The metal to metal affinity for the development of a cutting fluid should be measured so as to establish the ability of the cutting fluid to decrease the metal to metal affinity. Lengths of welded-zone measurements give an indication to what extent seizure occurs for the various cutting fluids. The extent of seizure is an indication of the metal to metal affinity of the cutting system.

By manipulating the chemical structure of the cutting fluid it is possible to decrease the metal to metal affinity and this is evident from the difference in cutting force and cutting temperatures that are observed as the welded zone length changes for different types of cutting fluids. A case study shows this. (Vieira, Machado, & Ezugwu, 2001) In this case study the cutting temperature, tool life and power consumption changed when the cutting fluid was changed.

If the cutting temperature and the cutting forces are monitored during cutting and the contact–zone length would change then a change in the temperature and the cutting force should be observed. Taking a cutting fluid that has a high affinity for the work-piece for example and a low affinity for the tool material should result in the two materials (i.e. the tool and the work-piece material) which may have a high affinity for each other ending up displaying a lower affinity for each other in the presence of the cutting fluid. This should become obvious from the length of the welded-zone during the metal cutting operation.

A change in the length of the welded-zone should show up in a lower cutting tool temperature, a smaller chip radius, a lower cutting force and a lower current drawn by the motor. A lower cutting force is expected for a shorter welded-zone because a shorter welded-zone implies less shearing of the metal.

The cutting tool often has a carbide or nitride coating on its surface. Both carbon and nitrogen have high electronegativities and are strongly bonded to the tool surface. This is also evident from the high melting points that carbides and nitrides have. A cutting fluid has constituents such as carbon, oxygen, sulphur, phosphor and chlorine and they are highly electronegative. Chlorine for example has an elecronegativity of 3.0 and that is twice that of aluminium. The electrons in the work-piece are less tightly held than those on the tool surface because they are in an environment of atoms of lower electronegativity, and consequently are easier to take. The cutting fluid serves to decrease the electron density in the surface layer of atoms on the work-piece the moment it comes into contact with the nascent metal surface as it is formed during cutting. The bond that a cutting fluid makes with the tool is less of a polar covalent nature than the bond it makes with a nascent metal surface because the atoms of the work-piece are less electronegative. The molecules of the cutting fluid should have a lesser tendency to cling to one another; thereby they would be freer to flow over the nascent metal surfaces and weaken the metallic bond in the vicinity of the cutting edge of the tool during metal cutting. The cutting fluids should have good wetting capability and because they should flow easily they would have a low viscosity.
By weakening the metallic bond the cutting forces should decrease and therefore the work that is performed in cutting should decrease. This should lead to a lower cutting temperature and consequently a smaller welded region and reduced tool wear.

The positive aspect of the electronegative atoms weakening the metallic bonds in the vicinity of the cutting edge is that they are able to do so without themselves being in the "sea" of electrons. By being on the surface of the metal they are able to draw or attract the electrons in the "sea" of electrons in the metal lattice. If however the atoms from the cutting fluid are able to penetrate the grain boundaries on the surface of the work-piece then the weakening of the metallic bond at a greater depth in the metal lattice is possible. The reason for carbon tetra chloride being such a good cutting fluid is that it has excellent wetting properties, flows very easily and has a high chlorine density. The small size of the molecule probably contributes to ease of penetration into the metal lattice. Other than the size of the molecules of the cutting fluid, the size of the atoms and the ease with which a cutting fluid supplies them to the cutting process must also play a role in the chemistry that happens on and near the surface of the work-piece

The dynamics of the cutting process are fast and the flow or movement of the metal from the work-piece continuously disturbs the cutting fluid. The metal that moves through the flow-zone typically does so in the time span of milliseconds as was shown in section 3.2. This means that it is very likely that no equilibrium conditions become established, but the cutting fluid present can still contribute to the success or failure of the cutting process.

A background knowledge of the relevant Miller indices (see Appendix A) for the tool and the work-piece material could help to shed some light on the reasons for some observations made for the cutting process. Another possibility in metal to metal affinity is that it is the degradation products from the cutting fluid itself that change the metal to metal affinity and that if any explanation as to why a certain cutting fluid performs better than another lies in the chemistry between the degradation products and the metals involved in the cutting process. These products often form by means of catalytic decomposition.

It is possible for tough, wear resistant metal carbides to form by catalytic decomposition of ethane. (Kajdas, 1996). Cutting fluids and or their degradation products can also be catalytically affected under high temperature and pressure, as in metal cutting. These degradation products could also be wear promoting. (Trent 1977) Cutting fluid formulation is therefore very important.

The theory that was put forward in section 2.1 about the chip/tool interface and about chip flow under conditions of seizure stated that shear occurs in the weakest material. This means that the work-piece is cut or sheared off at the tooltip/work-piece interface as it is the weaker material, but as the tool heats and the work material fuses to the tool in the seizure zone it becomes weak and if it so happens that the weakest link is at the boundary layer of the tool and shear zone, then the tool can lose mass to the chip during cutting.
There is also a diffusion gradient possible at the seizure zone and the tool can thus lose mass by carbide loss to the chip by diffusion. (Trent, 1977) Diffusion occurs at higher rates as the temperature of the metals involved increases, thus cooling should counteract wear on the tool. Other wear mechanisms such as adhesive wear and attrition wear are discussed by Trent (Trent, 1977).

On metal surfaces the unfavourable contribution to the total free energy may be minimised in several ways:

1. **By reducing the amount of surface area exposed**
2. **By predominantly exposing surface planes which have a low surface free energy**
3. **By altering the local surface atomic geometry in a way which reduces the surface free energy**

The interaction of the nascent metal surfaces and the surrounding atmosphere and/or the cutting fluids that are used will thus be such as to minimise the total surface free energy.

It should also be noted that there is a direct correspondence between the concepts of "surface stability" and "surface free energy" i.e. surfaces of low surface free energy will be more stable and vice versa.

One rule of thumb, is that the most stable surfaces are those with:

1. a high surface atom density
2. surface atoms of high co-ordination number

(Nix, 2002)
(Note - the two factors are obviously not independent, but are inevitably strongly correlated).

Consequently, for example, if we consider the individual surface planes of an fcc metal in vacuum, then we would expect the stability to decrease in the order

fcc (111) > fcc (100) > fcc (110)

but the presence of a fluid above the surface (gas or liquid) can drastically affect the surface free energies as a result of the possibility of molecular adsorption onto the surface. Preferential adsorption onto one or more of the surface planes can significantly alter the relative stabilities of different planes, but will none the less be such as to minimise the total surface free energy. These effects under reactive conditions (e.g. the high pressure/high temperature conditions pertaining in metal cutting) though poorly understood are to influence the ease of metal deformation, chip formation and metal to metal affinity.

6. The machinability of aluminium

The machinability of a material depends on:
i) the type of material being machined
ii) the cutting conditions
iii) the type of machining process that is used
iv) the type of lubrication and
v) the type of lubricant that is used.

The machinability of a material may be assessed by one or more of the following criteria: (Trent,1977)
i) Tool life. The amount of material that can be removed with a tool under standardised cutting conditions, before performance becomes unacceptable or before a fixed amount of tool wear is observed.
ii) Limiting rate of metal removal. The maximum rate at which a material can be machined for a standard short tool life.
iii) Cutting forces. The forces acting on the tool as measured by an appropriate method.
iv) Surface finish and dimensional accuracy. The surface finish and dimensional accuracy of the finished work-piece that are attainable under specified cutting conditions.
v) Chip shape. The chip shape as it influences the clearance of the chips from around the tool, under standardised conditions.

In this study the key factor is to reduce the operating costs for the metal that is cut and to optimise the uptime for the cutting process. This is achievable by increasing the tool life and by decreasing secondary machining time. This may be achieved by using limited volume lubrication and a suitable cutting fluid that enhances tool life and produces a smooth surface finish.

Tool life depends on a number of factors the most common being the cutting speed, the feed rate and the depth of cut. Fracture due to mechanical fatigue or snap loading and thermal fatigue are two other noteworthy contributors to tool failure particularly in operations of an interrupted nature such as milling and shaping for example. (Trent, 1977)

Aluminium and its alloys rate highly by most of the criteria for machinability. Aluminium melts at 659°C and its alloys melt at similar temperatures. The alloy used in this study is T6082 alloy. (See Appendix B) It is a heat-treatable aluminium-silicon-magnesium wrought alloy. and melts at 570°C ± 5°C. The temperatures generated during cutting are thus never high enough to damage heat treated structures of HSS (high speed steel) tools or the structures of the tungsten carbide tool. Good tool life can be attained when cutting most aluminium alloys up to speeds of 600m/min. when using carbide tools and 300m/min. when using HSS tools. (Trent, 1977) Similar cutting speeds for turning work are recommended for HSS by Le Grand (Le Grand 1971), but in drilling speeds of up to 1200m/min are recommended.

It is in aluminium alloys of silicon content above that of the eutectic composition that high wear rates become evident, even when using carbide tools. Wear is in the form of flank wear. The silicon structures other than the eutectic silicon contain large grains of silicon, up to 70 microns across. It is these large grains, when present, that are responsible for the pronounced increase in wear rate. The drastic effect of large silicon particles is the result of high stress and temperature that these impose on the cutting edge. The silicon particles have a high melting point (1420 °C) and quite a high hardness (> 400HV) The large silicon crystals cause an attrition type of wear (see next paragraph) and demonstrates that the wear of tools depends not only on the phases present in the work material, but also on their size and distribution. In the eutectic alloy the silicon particles are fine enough to pass the cutting edge without severe damage to the tool. The machining of high silicon alloy is one of the applications for diamond and diamond-coated tools.(Trent, 1977)

Attrition wear happens at relatively low cutting speeds, temperatures are low, and wear based plastic shear or diffusion does not occur. The flow of metal past the cutting edge is more irregular, less stream-lined or laminar , a built-up edge may be formed and contact with the tool may be less continuous. Under these conditions, fragments of microscopic size may be torn intermittently from the tool surface, and this mechanism is called attrition. (Trent, 1977) Aluminium is much softer than steel and because of the high hardness of tungsten carbide abrasive wear will not be considered here. Abrasive wear is much less likely with the tungsten carbide tool than with a high speed steel tool.

As far as the cutting forces for the machinability of aluminium alloys is concerned the tool forces are generally low and decrease somewhat when the cutting speed is raised.. High forces however do occur when commercially pure aluminium is cut. This is particularly so at low cutting speeds. In this respect aluminium behaves differently from magnesium, but in a similar way to many other pure metals. The area of contact on the rake face of the tool is very large. This leads to a low shear plane angle and very thick chips, with consequent high cutting force and high power consumption. The effect on pure aluminium of most alloying additions or of cold working is to reduce the tool forces, particularly at low cutting speeds because a eutectic is present when alloying has been done.

A built-up edge is not present when cutting commercially pure aluminium, but surface finish is poor except when very high cutting speeds are used. Most aluminium alloys have structures containing more than one phase and with these a built-up edge is formed at low cutting speeds.. When the cutting speed is increased to over 60 to 90 m/min., the built-up edge may or may not develop. Tool forces are low when a built-up edge is present, and the chip is thin, but the surface finish tends to be poor.

The main machinability problems with aluminium are in controlling the chips. Extensive plastic deformation before fracture, occurs more readily with face centered cubic (fcc) structure aluminium than with hexagonally plane centered (hpc) magnesium. When cutting aluminium and some of its alloys the chips are continuous, thick, strong and not readily broken. The actual form of the swarf varies greatly, but it may entangle the tooling and require interruption of the operation to clear the chips.

In some machine tools the designs can be modified slightly to prevent clogging as with the flutes of a drill for example. The cutting action can often be improved by modifying the rake and approach angles, or the introduction of chip breakers or curlers that deflect the chip into a tight spiral. The composition of the alloy can also be modified so as to produce chips that are fragmented and more easily broken. The standard aluminium specifications include 'free machining alloys' that contain additions of lead, lead and bismuth, or tin and antimony in proportions of up to about 0,5%. How these additions function is not certain, but the chips are more readily broken into small segments when they are present. These low melting point metals do not go into solid solution in aluminium, and are present in the structure as dispersed fine globules. They may act to reduce the ductility of the aluminium as it passes through the shear plane to form the chip. The main purpose of 'free cutting' additives in aluminium and its alloys is improvement in the chip form rather than better tool life or an increase in the metal removal rate.

7. Experimental preparation:

This chapter has the following layout:

- The type of machine tool that will be used is stated
- The choice of machine tool is motivated.
- The machine tool is described
- What parameters in the cutting process are to be measured, and how are they measured
- Other equipment, and analytical tools used are described.
- The software and communication with the cutting process is described.
- The choice of chip parameters is motivated and explained
- The choice of cutting fluids used is motivated
- The aim and significance of the experiments with reference to Appendix C is described.

The experimental setup and measurements

To evaluate the cutting process for various cutting fluids requires a test bench and a test method. A metal billet sawing operation is an operation where saw teeth engage in the work-piece intermittently, i.e. on each cycle the saw tooth has a time where it is cutting the billet and a time where it travels freely. The shaper (figure 2.3 & figure 2.4) was chosen as a test bench for the experimental work because it is easier to fit the instrumentation to this machine tool, without introducing as much noise as would be introduced on a sawing operation. This noise is with respect to the signals that are measured as an indication of the cutting force and cutting temperature. The measuring of certain cutting process parameters is necessary and they need to be analysed so as to show how different cutting fluids affect the cutting process. The main parameters that are measured and logged during the cutting process in this study are cutting force and cutting temperature. They give an indication of the success of the cutting process as discussed in the preceding chapters. The physical measurements of the properties of the chip after cutting are complementary to these parameters.

The other reasons why a shaper was chosen for the investigation were:

i) Motion is simple, i.e. forwards and backwards, not rotary. This circumvents complications with respect to the fitting of instrumentation that would otherwise have been experienced if a circular saw or band saw would have been used.
ii) to observe the effects generated during a single cut
iii) to keep cutting conditions as simple as possible, i.e. cutting in a single plane
iv) to use a straight tool edge, normal to both the cutting direction and the feed direction.
v) because it represents intermittent cutting

The shaper was built by Maskin Fabriks A.B. Thule in Malmö Sweden before 1980. It is a model S.16".S. The aluminium alloy that was cut was a heat treatable T6082 alloy. (see Appendix B for details)

The tool, in this case a tungsten carbide tool, is clamped in the tool holder on the shaper. The work-piece is stationary and the movement of the tool is simple. The electrical wiring for instrumentation to measure the cutting forces and the cutting temperature is therefore easily performed. For the tool/work-piece thermocouple that will be used for cutting temperature determination one wire needs to be attached to the tool and the other to the work-piece. This would have posed a more substantial problem if a lathe had been used, as the work-piece on a lathe rotates.

The tool is not electrically floating, but the work-piece is. One of the two must be floating otherwise the tool/work-piece thermocouple is in a dead short. The work-piece is electrically floating; i.e. it is insulated at the ends where it would have been in metal to metal contact with the shaper. The workpiece is clamped in the vice on the shaper such that the depth of cut will be constant over the length of the work-piece. This is achieved by machining a very thin layer off the top of the work-piece. After this the surface of the work-piece is parallel to the operating plane of the shaper. Because the movement of the tool is simple, it is easy to fit the strain gauge for cutting force measurement on the tool.

The simplified conditions applicable when doing laboratory investigations are known as orthogonal cutting and for this the tool edge is straight, it is normal to the cutting direction and normal to the feed direction. In figure 2.4 the push stroke is the cutting stroke and the force on the tool by the work-piece that is being cut has a moment about the bottom edge of the tool holder support. This moment maintains the tool down into the workpiece.

The **force** on the tool is the cutting force and it deforms the tool and the strain gauge mounted on the rake face of the tool. The amount of deformation of the strain gauge is an indication of the cutting force. The theory of strain gauges is discussed in detail by Hoffman (Hoffmann, 1989). The strain gauge is a type of "Wheatstone bridge". The resistance of the electrical wire changes as it is deformed and this affects the amount of current that can flow through that wire. The potential difference over the ends of this wire is amplified and the signal is logged on file by a computer program. The magnitude of this signal is directly proportional to the cutting force. The proportionality constant is determined experimentally. On the shaper this is the only force that needs to be considered. The feed force is zero because feed happens between cuts, and the tests are done with chip flow being equally restrained from both sides. The force to keep the tool down into the workpiece is provided by the moment the cutting force has about the tool holder support. The only force that needs to be measured to evaluate the cutting process therefore is the cutting force. It is evident that the cutting process has been simplified very much to facilitate ease of data- acquisition, monitoring and analysis.

The **temperature** in the metal cutting process is measured by means of a tool/workpiece thermocouple. The theory of thermocouples is discussed in detail by Considine. (Considine D.M., 1974) A thermocouple consists of two dissimilar metals, which in this case are the tool and the workpiece. A temperature dependent thermo-electric e.m.f. (electro motive force) is generated at the junction of the dissimilar metals. This e.m.f. signal is measured amplified and converted to a temperature reading that is logged on file for later analysis. The calibration curve for the tool/workpiece thermocouple is determined experimentally.

As far as the use of the thermocouple effect for monitoring of the cutting process is concerned there are two cold junctions and one hot junction in the circuit. The two cold junctions are approximately 100mm removed from the hot junction. They are, and essentially stay at room temperature; namely 23 °C. The change of e.m.f. that would be generated if the cold junction temperatures were not constant would have to be compensated for by referencing the obtained signal to the e.m.f. that is measured at ambient temperature prior to beginning experiments. The voltages of the cold junctions would have to be added to the signal obtained during experimenting (Considine, 1974) and Capgo, 2002) to obtain the true e.m.f. that is generated relative to room temperature.

Cutting speeds in metal cutting are usually between 3 and 200 m/min., but in exceptional cases can be higher than 3000 m/min. Cutting speeds and rate of metal removal vary and depend on many factors such as:

- cutting conditions
- the type of metal that is cut
- the cutting fluid that is used and
- the type of tool and type of machine tool that is used.

Metal removal rates of nearly 0 cm^3/min. to about 1600 cm^3/min. (Trent, 1977) are encountered in metal working operations. In this study the rate of metal removal was 2.2 cm^3/min. and the range of cutting speeds available on the shaper ranged between 5.7 m/min. and 90m/min. All the experiments that were performed with cutting fluid were performed at 8m/min. A few experiments for dry cutting were done to show the influence of cutting speed on the temperature and cutting force response of the cutting process.

Other equipment and analytical tools

The optical microscope and the scanning electron microscope (SEM) are valuable in making micrographs by which analysis of the chips for metal deformation and flow-zone thickness may be performed. The optical microscope is used to make micrographs of etched cross sections of the chips. The Vickers hardness test machine is used to determine the micro-hardness profiles on the chips. The hardness profiles are complementary to the micrographs as far as determining the flow-zone thickness is concerned.

A non-etched chip sample as cut can be analysed by means of a scanning electron microscope (SEM) and/or mass spectroscopy (MS) for type of atoms that are present on the underside of the chip surface and in the chip after cutting when good cutting results are obtained. For an analysis inside the chip a longitudinal cross section should be used. By examining the cross-section of the tool work-piece interface, the work-piece finished surface, and the tool surface after cutting, under a (SEM) important information might be obtained. A SEM analysis requires extreme vacuum, and has the advantage of a great depth of focus. Two to three layers thick of atoms can be seen. If there are traces of the constituent atoms of the cutting fluid used on these surfaces then it may be possible to postulate what happened with the chemistry. The postulate might be difficult to prove.

Likewise examining the tool cutting edge and rake face by SEM, or mass ion spectroscopy (MIS) could give an indication of which atoms are present. This could give an indication of which atoms are desired, when this examination occurs after pleasing results from a mechanical parameter investigation are obtained. If more detail is required FTIR (Fourier transform infrared) spectroscopy can be used for identification of the metal compounds that do form.

The computer applied cutting fluid for one second before every test was started and then the moment the cutting tool made contact with the work-piece temperature measurement started and this signal was used to trigger the application of cutting fluid for the rest of the duration of the cut. The applicator that was used is a mist type applicator, in which a pulsating pneumatically operated piston pumps the cutting fluid into a mixing chamber in which the cutting fluid is broken up into minute droplets and mixed with air under pressure. A jet of air/cutting fluid mist is applied to the flow-zone area in the cutting process.

For the purpose of the study of the aluminium cutting fluids a Surtronic 3P profilometer is used to determine surface roughness. (Hobson,1980). A Vickers hardness tester is used with a chart to express the Vickers hardness (VH25) before and after cutting. (Van der Voort., 1999/04)

Software

All the software that was needed to perform the experiments was self-developed. A program was written so that the sampling rate could be changed if deemed necessary. The sampling rate was however fixed at 200 ± 2Hz for all the experiments that were performed. For some unknown reason the sampling frequency varied within 1% of 200 Hz.

The instrumentation was purchased and self installed, except for the strain gauge. A PC30B A/D – D/A converter card was used for analog to digital and digital to analogue signal conversion, and two signal amplifiers were used to amplify the temperature and cutting force signals sufficiently for use in the PC30B card. The system that was constructed may be schematically represented as in figure 7.1. The software is necessary for establishing communications between the measuring sensors, (i.e. the tool/work-piece thermocouple and the strain gauge), and the computer.

Once the hardware had been installed software had to be developed and the measuring instruments and signal receiving components had to be calibrated. For the PC30B card that was used, calibration requires a high precision voltage source and a high precision multimeter. For calibration details use was made of the appropriate card user manuals (Tinker, 1990,1992). If the cards are used often it is necessary to check their calibration

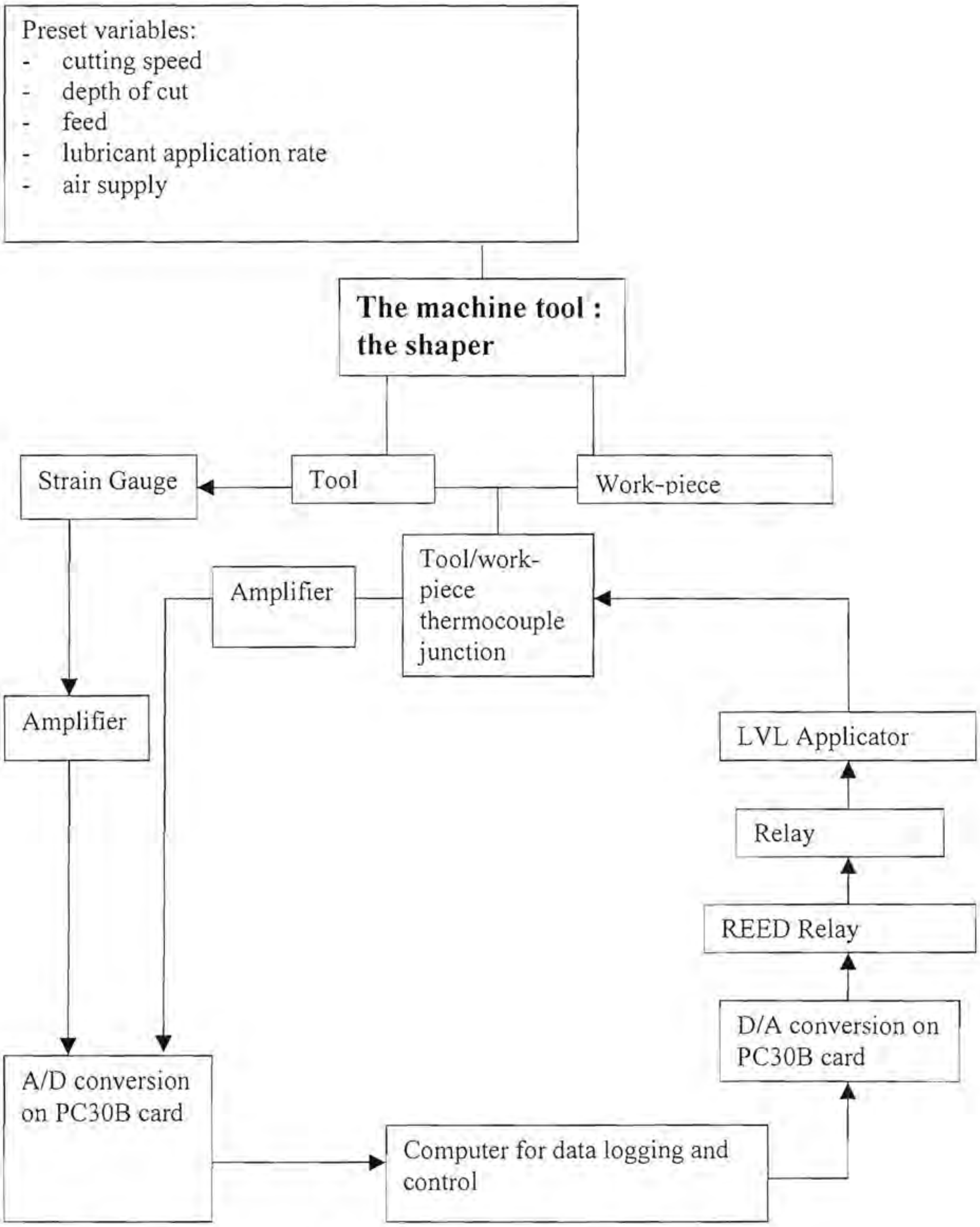

Figure 7.1 The Shaper machine hardware and data acquisition set-up

from time to time. It is important that the board is jumpered into its intended operating mode when calibration is done. The calibration software program cal.exe under C:\pc30, is run when calibration is to be done.

Establishing communications between the process hardware and the computer also requires wiring and an AD/DA card. This card requires a voltage input signal and gives a voltage output signal. The signal comes from amplifier via the measuring element on the shaper to the PC30B card. The signals come into the card as analogue voltage inputs and are converted to 12 bit digital code. More details on what needed to be done to set up the communication for the cutting process are in Appendix E.

Experimental planning

The experiments are described later and in detail in Appendix C. The **cutting force** and the **cutting temperature** in metal cutting should be measured as they give an indication of conditions during cutting. If the welded zone is large the cutting force and cutting temperature are expected to be higher than when it is smaller, because more metal will have to be sheared per unit time. The sudden decrease in cutting force with an immediate decrease in cutting temperature following should indicate that a built-up edge has formed. The length of the chip radius and the thickness of the chip should also decrease when this happens. The temperature and the cutting force measurements are very important for the cutting process experiments because many of the other parameters that were monitored were determined from cutting force and temperature data as will be shown later in this chapter.

The metal-to-metal affinity for the development of a cutting fluid should be measured so as to establish the ability of the cutting fluid to decrease the metal to metal affinity, and thereby decrease tool wear. The chip mass should be standardised because chip mass has a pronounced effect on the cutting force and cutting temperature. This means that all cuts that are performed can be compared to dry cuts or any other reference cutting fluid under the same cutting conditions. The built-up edge should not be present in the region of the cut where the comparison is made, because it is a dynamic unstable structure that changes the cutting conditions. Length of welded-zone measurements from quick-stop sections, although tedious to do, give an indication of the extent of seizure that occurs for various cutting fluids. The extent of seizure is an indication of the metal-to-metal affinity of the cutting system.

Another idea on how the length of the welded-zone may be determined is by using restricted contact tools and finding the **contact length** at which the cutting force starts to decrease for standardised cutting conditions.

Bi-directional chip flow restraint is used. This produces chips that are two dimensional that are sufficiently open when a built-up edge is not present that their surfaces may easily be inspected and their length easily determined.

In all the experiments performed, a relatively shallow cut of 0.25mm and low cutting speed of 8 m/min. will be used, so as to be able to build in a fair amount of sensitivity to the cutting fluids that are used. This should result in shorter thicker chips and this is on the **steep part** of the shear strain vs. shear plane angle relationship graphically presented in figure 2.9. Differences in shear strain for the different lubricants used should therefore be more evident than when a higher cutting speed is used that produces longer, thinner and less strained chips.

As **surface finish** is a major objective in metal cutting and lubricants are rather more effective at low cutting speeds in the presence of a built-up edge (Trent, 1977) a low cutting speed was chosen for the experiments that were performed.

A shallow cut is used so that if there is lubricant penetration into the cutting zone from the sides where the lubricant is applied then the area affected by the lubricant as a percentage of the total area of the cutting zone will be more significant than when a deeper cut is made.

It is postulated that the e.m.f. that is generated during cutting will decrease as there is a built-up edge that is forming and then suddenly increase again if the built-up edge is sheared off. The maximum temperature occurs in the flow-zone and the flow zone moves away from the tool rake face as a built-up edge forms. It also decreases in length in the same way as it decreases in size/length when a restricted contact tool is used to cut the metal. This decreases the amount of shear that takes place when metal cutting is done, hence the e.m.f. that is generated between the dissimilar metals i.e. between the tool and the work material decreases when a built-up edge forms. The results from the experiments will help to substantiate this claim.

It is thought that the key to the chemistry involved lies in the role that the reaction products from the cutting fluid play in reducing the metal-to-metal affinity. Metal-to-metal affinity should be reduced as much as possible to prevent a large welded region in the contact-zone.

The current vs. depth of cut that is drawn by the electric motor during cutting could also be monitored in the experiments. It was decided not to do this as this is not as sensitive a method as using strain gauges, thus strain gauges were fitted to the cutting tool and cutting force in the direction of cut was monitored. The problem with the electric motor and data sampling was the associated complications in sampling.

CHOICE AND MOTIVATION FOR CHOICE OF CHIP PARAMETERS

The **average smooth fraction** on the underside of the chips will be determined. This should give an indication when stick-slip initiates and is an indication of the distance cut until seizure starts to appear. Little fine scratches on the underside of the chip should form as the chip welds to the tool face and shears loose. The better a cutting fluid, the longer the cut that can be made without stick-slip occurring.

The **shape** of the chips will be observed because the shape, the **chip radius** in particular, is an indication of when a built-up edge forms. The built-up edge will change the rake face angle and the chip will have a shorter chip radius when this happens. The cutting force will decrease as a built-up edge will act as a restricted contact tool and the chip should become thinner.

The **length of cut until the first break** in the chip occurs will be measured because it is expected that this is related to the length cut until the built-up edge forms. It is expected that the chip will break soon after the built-up edge forms. When the built-up edge forms the chip is very much more deformed as is seen from the smaller chip radius and therefore more strain-hardened and this often leads to the chip breaking under the compressive stress. It is expected that the chip will be harder when cutting with a built-up edge than cutting when the built-up edge is not present.

The **chip shear strain and the hardness and the hardness profile** for the chip in the non-built-up edge region will be determined on a Vickers hardness tester. From the chip shear strain and the average hardness in the almost flat region of the hardness profile for the chip **the ease of chip formation** may be calculated. It is expected that the easier a chip can form and the softer it is, the less tool wear should result. To be able to confirm that the built-up edge does cause a harder chip a hardness profile on one of the chips where a built-up edge was present should be performed. The hardness profile for a chip should also serve to indicate the thickness of the flow-zone and is complementary to the SEM micrograph and the optical micrograph of an etched cross section of a chip. The thickness of the flow-zone is determined because it should reflect on the ease of deformation in the chip and the temperature that is attained at the interface of the tool and the flow-zone. If ease of deformation in the chip is high and or the temperature is high then a thicker flow-zone should be seen.

The **peak cutting** force normalised for a 200 mg chip will be determined from the cutting force data as it might be able to show a trend that is related to other cutting process parameters for a cutting fluid.

The **peak average temperature** prior to formation of the built-up edge will be determined from the cutting temperature data, as it should point out the maximum temperature up to which a cutting fluid can prevent the formation of a built-up edge.

The **five point moving average of the cutting force** prior to built-up edge formation should serve as an indicator of the contact length and the ease of chip formation at that stage of the cut. The relative contribution of these two parameters to the cutting force will however be unknown. If the contact lengths would be determined for that stage of the cut, then they could be used together with the ease of chip formation data in the interpretation of the cutting force data at that stage of the cut.

The aluminium plate that will be cut in the experiments must be marked at the ¼- , ½- and ¾- way mark so that the length of the first quarter of the chip may be determined easily and used in the calculation of the **chip thickness ratio** that will also be used for the calculation of the **chip shear strain** and the **shear plane angle**.

The **repeatability of the chip masses** will be noted for control purposes, and so that if there is a difference in the repeatability of the chip mass for different cutting fluids that this difference will be evident.

The **cutting temperature at the one quarter way mark** of the length of cut will be determined from the temperature data because it is a function of the contact length and the thickness of the flow-zone which itself is affected by the ease of chip formation and the temperature at that stage of the cut. The longer the contact length the greater the area for heat exchange with the tool, consequently the tool should heat up faster. This cutting temperature is a parameter for which the individual contributions of the contact length and the flow-zone thickness will be unknown. The complicated question is: What is the temperature in the flow-zone at the quarter way mark, and has the tool/flow-zone interface attained this temperature or not? Does the tool heat up faster due to a larger temperature gradient or due to a larger surface area for heat exchange?

Take it that the temperature for two different cutting fluids in the volume of the flow-zone above the welded zone is the same, and that the volume of the flow-zone above the welded zone is also the same. The cutting temperature at the quarter way mark would be higher for the cutting fluid with the longer welded zone because it has a larger area for heat exchange with the tool rake face, despite the fact that the temperature in the flow-zone for both cutting fluids is the same. Although this is complicated, it is desirable that the tool must be as cool as possible, and therefore the temperature at the quarter way mark is determined as a performance parameter dependent on the cutting fluid.

The **surface finish** for the different cutting fluids will be determined as a cutting fluid that produces a smoother surface finish will require less secondary machining time and this is economically desirable.

SELECTION OF CUTTING FLUIDS

The types of cutting fluids that are to be tested in this investigation are selected from a range of known types of chemistries that are, or can be used as cutting fluids. This was done so that the bench test can show the differences in cutting performance between different chemistries. More than one example of some cutting fluids with similar chemistry was chosen so that the bench test can show if there are similarities between related cutting fluids. The chemistries chosen include alkanes, esters, polyisobutylene, carbon tetra chloride (CCl_4) and dry cutting.

Dry Cutting

Dry cutting is performed as a reference against which the other cutting fluids may be compared.

Alkanes

Alkanes are widely used as cutting fluids and it is known that paraffin may also be used as a cutting fluid when cutting aluminium. Usually the alkanes are chlorinated to improve their cutting performance and they are then referred to as chlorinated alkanes or chlorinated paraffins. Chlorine is an undesirable constituent of cutting fluids because the reaction products may be carcinogenic and because they contribute to skin disorders related to cutting fluids.

Generally the trend for cutting fluids that contain chlorinated paraffins is that the rake face and or flank face temperature decreases, and or the rate of flank wear and built-up edge formation decreases (Birmingham, Henshall & Hooper,1997). Work performed in that investigation was for intermittent cutting with a HSS tool.

Esters

Currently esters are used more and more as cutting fluids because they do not cause skin problems and have a higher thermal range across which they can be used as cutting fluids, i.e. they are thermally more stable than the alkanes. The ester linkage is an exceptionally stable one; bond energy determinations predict that it is more thermally stable than the C-C bond. (Mortier & Orzulik, 1993). Ester groups are polar and will therefore affect the efficiency of anti-wear additives.

When a base fluid that is too polar is used it and not the anti-wear additives cover the metal surfaces. This can result in higher wear characteristics. Consequently, although esters have superior lubricity properties compared to mineral oils, they are less efficient than anti-wear additives.

Esters can be classified in terms of their non-polarity. (Van der Waal,1985)

$$\text{Non-polarity index} = \frac{\text{total number of C atoms x molecular weight}}{\text{number of carboxylic groups x 100}} \qquad \text{Eqn.7.2}$$

In general the higher the non-polarity index, the lower the affinity for the metal surface. Using equation 7.2 shows that increasing molecular weight will generally improve overall lubricity. Esters terminated by normal acids or alcohols have better lubricities than those with branched acids/alcohols, while esters with mixed acids/alcohols have lubricities intermediate between esters of normal acids and esters of branched acids/alcohols. (Mortier & Orszulik, 1993)

PIB's

Poly-isobutylenes (PIB's) contribute to forming a tough lubricating film even under severe conditions and provide excellent protection against wear and scuffing. They are also suited for high temperature applications. They also have the ability to burn off cleanly. The above properties make them suitable as a metal working fluid.

Like the esters, a metal cutting fluid free of chlorine is obtained. Other than the esters, PIB is not biodegradable and this may limit its use in some applications where environmental issues are significant. In limited volume lubrication any residual PIB on the chips can be burnt off easily during recycling and PIB in metal cutting therefore has merit.

CCl_4

Carbon tetra chloride is known to be a good cutting fluid (Liew, Hutchings & Williams, 1997; Trent, 1977; Boston,1952), and it is therefore tested as a matter of confirming this, and for comparing the other cutting fluids that are tested. Carbon tetra chloride is however not used as a cutting fluid because it poses a threat to the health of the machine tool operators; it is carcinogenic and can cause permanent damage of the kidneys. By the choice of this cutting fluid a reference against which the chlorine free cutting fluids may be compared is obtained.

Experimental procedures

Before the execution of any experiments the following must always be checked:

- Fix the reference points namely 0.33 ± 0.01V at 23°C for temperature data accumulation and -0.005 ± 0.005V for 0N on the strain gauge. These readings are adjusted by tuning the trimpots on the signal amplifiers so that the signals obtained for 23 °C and 0N meet the requirements. The temperature signal is always an unfiltered signal, but the force signal is obtained with the filter on the signal amplifier in the "on" position.

A detailed explanation of how to perform the following experiments is given in Appendix C.

Experiment 1:
Aim: To see whether an e.m.f. will be generated merely by the deformation of the metal crystal structure.
Significance: If an e.m.f. would result merely by the deformation of the metal lattice structure then compensation for this fraction of the observed e.m.f. would have to be made so as to obtain the true e.m.f. that is due only to the thermo-electric effect.

Experiment 2:
Aim: To obtain data to calibrate the tool/workpiece thermocouple. This gives an indication of the temperatures that are attained when the aluminium is being cut.
The temperature is measured by using the dissimilar metal junction formed by the tool and the workpiece as a thermocouple. The e.m.f. that is generated at this junction is an indication of the temperature at the junction, i.e. the temperature is a function of the e.m.f.
Significance: If the temperature and the corresponding e.m.f for a number of temperature s between 30 °C and the melting point of the alloy is known then the temperature e.m.f. relationship may be determined by mathematical regression. This relationship can be implemented directly in the computer program so that the temperature corresponding to the generated e.m.f. can be displayed on screen and written to file. Comparisons between cutting temperatures rather than e.m.fs for different cutting fluids can therefore easily be made.

Experiment 3:
Aim: To obtain data to calibrate the strain gauge.
Significance: If the milli-volt signal and the corresponding force on the cutting tool for a number of forces is known then linear regression will give the relationship between the milli-volt signal and the cutting force. This relationship is then implemented in the computer program so that the cutting force for the particular milli-volt signal can be displayed on screen and written to file. Comparisons between cutting forces rather than milli-volt signals for different cutting fluids can therefore easily be made.

Experiment 4:
Aim: To obtain chips and the corresponding cutting force and temperature data for cutting metal when various cutting fluids are used.
Significance: By collecting the chips and their cutting force and temperature data analysis of the cutting process for a particular cutting fluid can be performed. The temperature and cutting force data together with the physical parameters that are measured on the chip, provide important information on the success of the cutting process. The important physical parameters on the chips were mentioned in the introduction. The chip masses are determined first. This is important because chip mass has a profound effect on the cutting force and temperature data. This way meaningful comparisons of parameters for the various cutting fluids may be made. Once the mass has been controlled the physical parameters of the chips may be determined as described in Appendix C. Thereafter analysis of the chips is performed.

Experiment 5:
Aim: To obtain surface roughness data for the different cutting fluids that were used.
Significance: Surface finish in metal cutting is an important parameter. A smoother surface finish requires less secondary machining time and the finished product can therefore be produced at a lower cost.

Experiment 6:
Aim: To show an etched micrograph of the built-up edge that is present and to show its affect on the micro-hardness profile for the chip.
Significance: The micrograph serves as visual confirmation that the built-up edge is present. The hardness profile shows the effect of the built-up edge on the strain hardening of the chip.

Experiment 7:
Aim: To see whether the built-up edge forms later, i.e. at a greater length of cut, when the cutting speed is increased and to see the effect of this on the cutting temperature and the cutting forces.
Significance: This experiment shows at which cutting speed and cutting temperature the shear rate becomes such that the built-up edge can no longer form. It also shows how the contact length and cutting force and cutting temperature increases when the built-up edge is not present.