8. Results and Discussion

Results from the cutting process

Nine different cutting fluids were tested including dry cutting. Ten cuts were made for every cutting fluid that was tested, of which five or six are shown per cutting fluid in Appendix D. The exception was for the dry cutting tests where thirty-five cuts were made so that comparable chip masses were available for the cuts performed with cutting fluid.

Experiment 4 (detailed in Appendix C) is the most important experiment and hence its results are presented first. The preceding experiments were necessary to establish the procedure and to set up the equipment so that experiment 4 could be performed. Results for those experiments are in Appendix C, and were used to calibrate the tool/work-piece thermocouple and the strain gauge that was used.

The first result is for carbon tetra-chloride and it shows by means of arrows, which graph **represents temperature** and which graph **represents cutting force**. This is shown once only and is relevant for all similar graphs that follow under the raw data column for each individual cutting fluid that was tested.

It must be noted that all results are **referenced to dry cuts** of comparable chip mass and that the reference graph is always the **dark coloured graph**. The chip mass must be comparable because chip mass has a profound effect on the cutting process data.

All the graphical results have a title per graph and this title aims to convey some more background information of the test to the reader. A title is discussed here for clarity of how the titles should be read. Take for example the following titles:

1) SC T3 C.force and Temperature 200 mg
2) Compare C.forces C3 200 vs. Dry2 198mg
3) Compare Temperature C3 200 and Dry2 198mg

The first title conveys that it was the third test that was done for cutting fluid sample C, hence SC T3, and that the cutting force and the temperature data for this cut are displayed, and that the mass of the chip was 200 mg.

The second title conveys that cutting force data for the third test of sample C of chip mass 200mg is compared to the second dry cutting test with a chip mass of 198mg.

The third title conveys that the temperature data of the third cut for sample C of chip mass 200mg is compared to the second dry cutting test with a chip mass of 198 mg.
The two to three mg mass difference for the chips that are compared, is due to the chip that was cut with cutting fluid being wet. It was found that a dried chip had a mass of about two-mg less than a wet chip after cutting.

The graphs shown in Appendix D are arranged in three columns. The graphs in column one are the raw results. In column two a five point moving average of the cutting forces is presented and in the last column the temperature comparisons are presented. Furthermore, the results for a particular number of test are displayed in the same row of graphs, i.e. the third test for cutting fluid sample A, for example, is displayed in the third row of graphs for sample A.

In viewing each of the sets of graphs of the cutting fluids that were tested on the shaper it is apparent that there is a high degree of repeatability of the results. Each cut is 205mm long. The duration of each cut at 8m/min. is 1,55 seconds. At 200 Hz sampling rates therefore about 310 data points are available for each cut when a cutting speed of 8m/min is used. This is equivalent to one data point or one sample every 5 milliseconds. The x-axis in the graphical results is the sample number and essentially constitutes a time scale. To convert sample number to time divide the sample number by the sampling rate.

The distance cut in 5 milliseconds is 0.66mm. The rate of cutting fluid application in each test was 0.2 ml/min and the amount per cut of 1,55 seconds is thus slightly more than 5 micro-liters.

The different cutting fluids that were tested were:
- dry cutting
- carbon tetra-chloride
- paraffin as common illuminating paraffin
- a light fraction and a heavy fraction alkane
- three different types of esters and
- poly-isobutylene

The reason for this selection was given under the experimental planning section

For every cutting fluid the graph for cutting force first rises very rapidly to a maximum and then rapidly decreases slightly. (Figure 8.1 and figure 8.2) Initially the cutting force is low because the workpiece material is ductile and soft, but metal accumulates very rapidly in the chip that forms and the chip formation zone rapidly increases in size from $0mm^3$ to close to its maximum size. As the chip formation zone and the chip volume increase the cutting force increases. The metal is still cold and has not reached its maximum temperature yet (Figure 8.1 and figure 8.3), and is therefore severely cold-worked and strain hardened. This is when the maximum cutting force is observed.

As metal cutting continues, the temperature rapidly approaches the maximum and the metal in the chip formation zone becomes softer and a corresponding decrease is seen in the cutting force. The cutting force would stabilise then if the contact length could stay constant, but instead the maximum temperature for the cut is reached and metal to metal affinity increases resulting in metal welding/seizure.

In this case a rapid metal build-up occurs on the welded length/ contact length resulting in built-up edge formation (Figure 2.12). When a built-up edge forms the effective rake face angle changes. The tendency is towards a more negative rake face angle. This results in increased chip strain, as is evident from figure 2.9 and as will be shown in the micro-hardness test that was done for poly-isobutylene where chip formation occurred in the presence of a built-up edge. It also results in a restricted contact. This is like the tool in figure 3.2. A shorter contact length results in a shorter flow-zone and therefore less shear and therefore a further decrease in cutting force and temperature is observed. The built-up edge is however not a stable structure and can shear off unpredictably to varying extents.

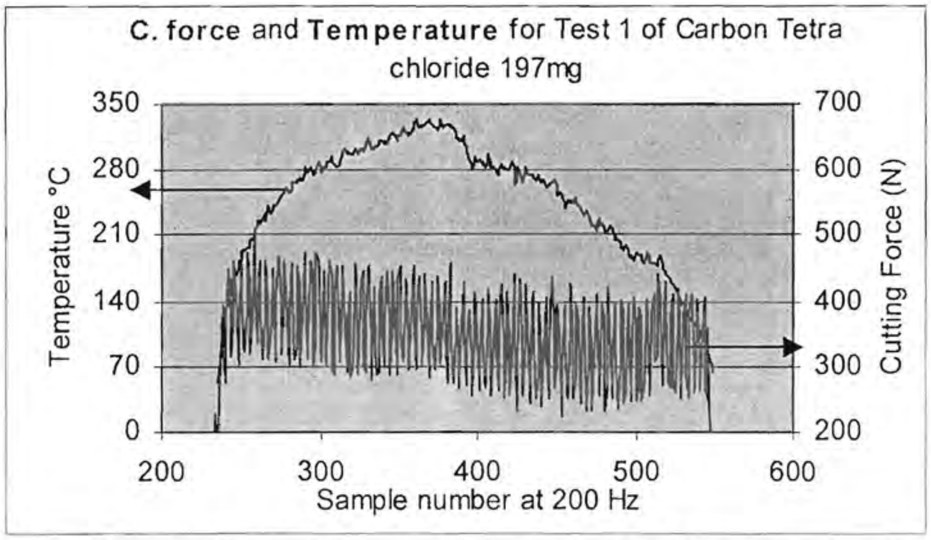

Figure 8.1 General form of the graphical results for the raw cutting force and temperature data

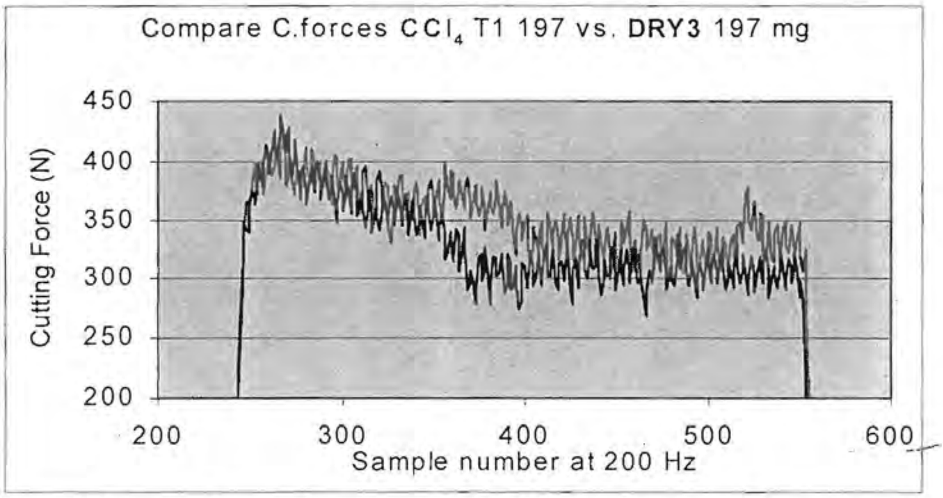

Figure 8.2 General form of graphical result of five point moving average for cutting Force

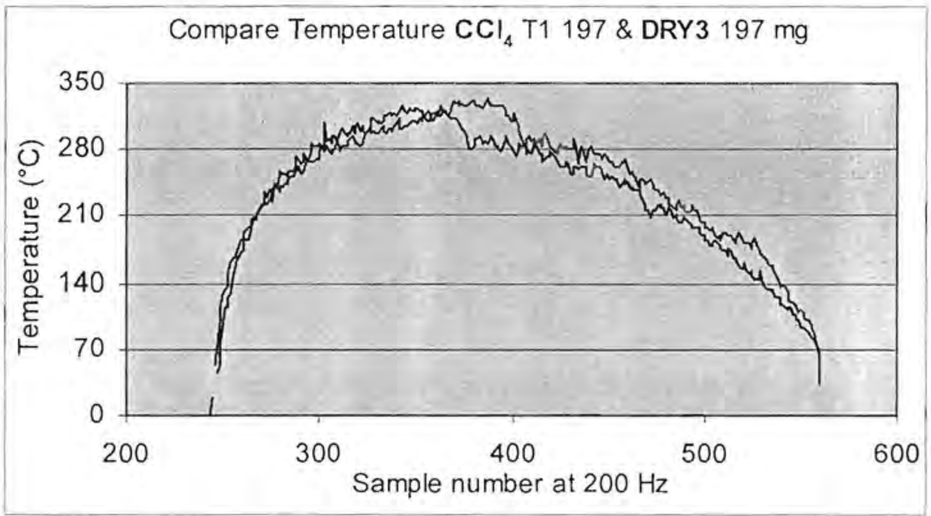

Figure 8.3 General form of graphical result for the temperature response

This is like having a tool for which the cutting geometry is forever changing and leads to a fluctuation of results during metal cutting. The efficiency of a metal cutting operation is also dependent on the tool geometry and therefore the built-up edge is unacceptable.

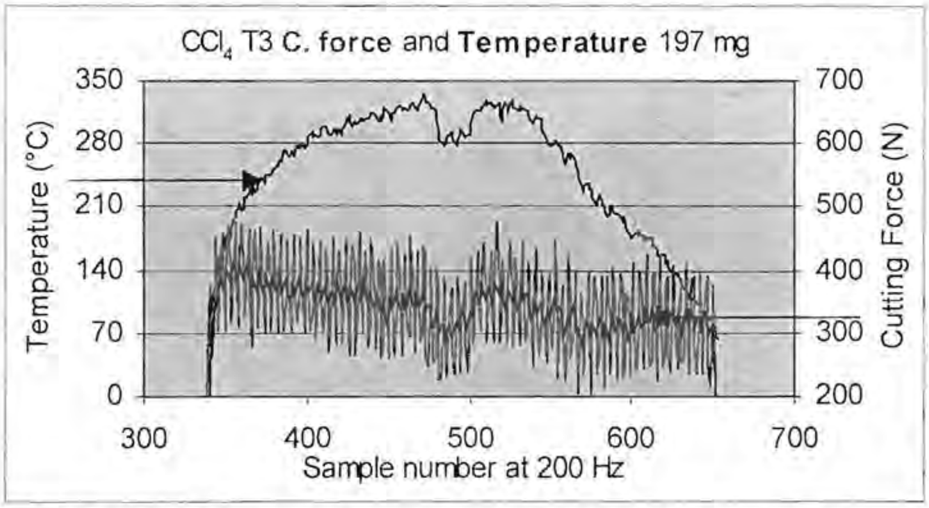

Figure 8.4 Temperature and cutting force response when a built-up edge forms and is sheared off and forms again.

In figure 8.4 the same initially happens as with the other cuts that were made, but about half way through completing the cut a built-up edge forms and the cutting force decreases rapidly and the temperature decreases immediately afterwards. This shows that the temperature response for the cut lags the cutting force response, but only slightly and this is probably more evident from when the cutting force suddenly increases again thereafter.

The dark curve in the middle of the cutting force of figure 8.4 is a superimposed 5 point moving average of the cutting force and emphasises the change in cutting force when a built-up edge forms or is sheared off. Immediately after the built-up edge had formed it was sheared off again and the cutting force immediately increased and immediately afterwards the cutting temperature increased as well, only to steadily decrease again thereafter as the build up of a new built-up edge started.

That the temperature lags the cutting force also makes sense from a dynamic point of view, since the dynamics of force measurement should be faster than that of the energy measurement via temperature of the tool/work thermocouple.

It is important to remember that temperature measurement is by means of the tool/workpiece thermocouple and is measured at the junction of the dissimilar metals. The observed temperature when a built-up edge forms will therefore decrease because the flow-zone is slightly removed from the dissimilar junction as it is situated on top of the built-up edge.

The flow-zone has a very high area to volume ratio and as metal, especially aluminium, is a very good conductor of heat, this facilitates very efficient heat loss from the flow-zone. All three components necessary for efficient heat transfer are present namely good conductivity, a large temperature gradient between the flow-zone and the surrounding metal and a large surface area. This is evident from very large temperature gradients that exist at and around the flow-zone. (See figure 4.4 for a temperature profile on the tool when steel is cut) Further away from the flow-zone the temperature gradient becomes less steep because the volume of metal into which the heat is dissipated increases. Evidence for the steep temperature gradients may be found from optical micrographs taken after etching the tool and from micro-hardness tests done on high-speed steel tools. The hardness and the change in the metal structure at and near the rake face of the tools after metal cutting is indicative of the temperatures that were present for the structures to form.

It must be pointed out that the time interval for a change in temperature in the flow-zone is very short. This is evident from figure 8.3 for example, (and all other temperature graphs), where it is noted that at a sampling interval of 5 milliseconds, significant temperature changes are sometimes seen over intervals of ± 10 to 20 milliseconds, as for example when a built-up edge forms. This shows that the tool-workpiece thermocouple has very fast dynamics.

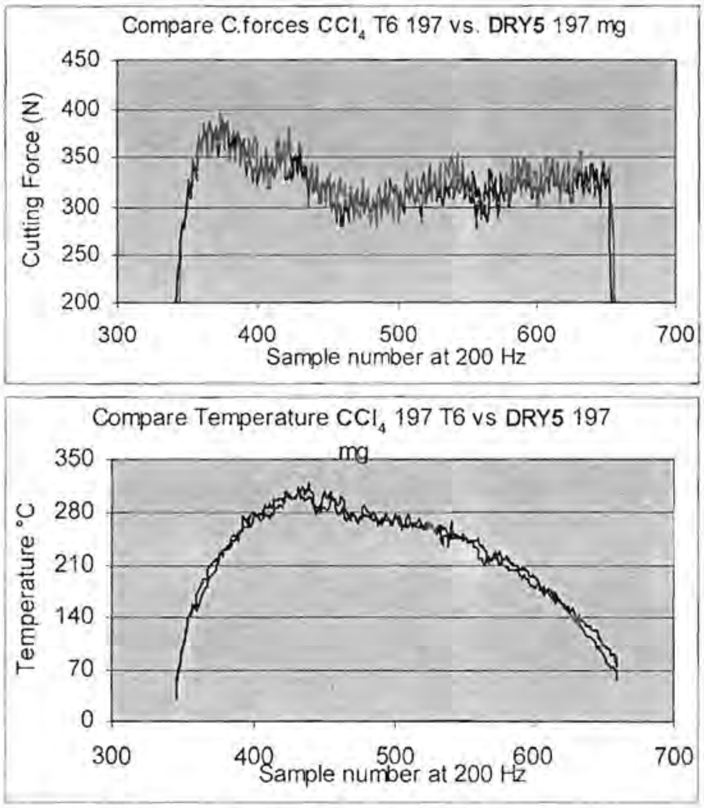

Figure 8.5 Graphical evidence that lubricant application failed

Another interesting observation is the fact that the cutting force signal fluctuates much more than the temperature signal. The temperature signal is an unfiltered signal whereas the cutting force is a filtered signal. The reason for the cutting force signal fluctuating so much is because of the three phase alternating current motor, (a.c.motor). The motor

cannot supply a constant force, i.e. the force varies with the 50Hz sine wave of the a.c. current, thus the oscillations in the cutting force that is recorded are at 50 Hz
The temperature signal has very little noise because good electrical contact at the cold and hot junctions was ensured.

In figure 8.5 it is seen that the cutting force and the temperature for a dry cut and a cut performed with CCL_4 are very similar, yet when comparing the result to that of figure 8.2 and figure 8.3 there is a significant difference between the cutting force and temperature for dry cutting and CCl_4 cutting, i.e. the cutting force and temperature curves lie further apart. The comparison must be done for data points that lie vertically above each other. From this comparison it should be clear that lubricant application malfunctioned for the test performed for figure 8.5. The built-up edge for CCl_4 also formed later in figure 8.3 than in figure 8.5.

It was stated under the experimental planning section that the chip mass must be determined after a cut is performed before the determination of the physical chip parameters and that the masses of chips that are compared for different cutting fluids must be the same. This was so because chip mass significantly increased the difference in cutting force as is evident from figure 8.6. The cutting force was more than 20% lower for the lighter chip and, although not shown here the temperature that was recorded, was also lower. A decrease in the amplitude of oscillation for the cutting force was also noted for a lighter chip.

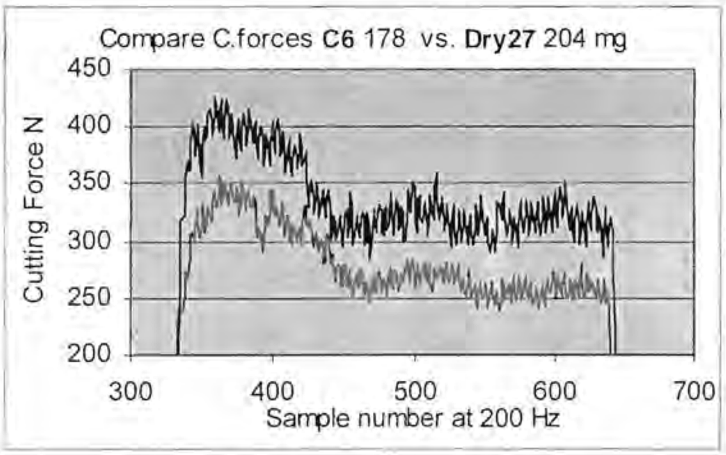

Figure 8.6 Difference in cutting force due to difference in chip mass

In figures 8.1 to 8.6 the pronounced decreases in cutting force and corresponding temperature, depending on which graphical result is considered, is clearly visible. The sudden decrease in cutting force **and** temperature signals that a built-up edge has formed, and when the chip radius and/or the chip thickness ratio for that stage of the cut also shows a sudden decrease it helps to confirm that the built-up edge has indeed formed.

The length cut to formation of built-up edge parameter in Table 8.1 was calculated from the graphical results. In figure 8.6 for the dry cut for example, approximately (430-330) i.e. 100 samples had been taken when the cutting force decreased markedly. The same is seen on the temperature response for that particular cut. (See the sets of results for the individual cutting fluids in Appendix D, where the results for sample C are given).

The total number of samples taken in the cut are 311. The length of each cut was 205 mm and in this case the product of 100/311 and 205mm gives the length cut until the built-up edge forms. For the particular cut of Dry27 the built-up edge formed at a distance of 66mm. Applying the same method to calculate the distance cut to formation of built-up edge for CCl_4 in figure 8.2 and figure 8.3 gives a distance of $((380 - 240)/311)*205 = 92$ mm.

Once the built-up edge has formed, no comparisons of the graphical results should be made between the different cutting fluids for that region, as the built-up edge is an unstable continuously changing and thus unpredictable structure, i.e. all comparisons must be done for the non-built-up edge region.

The built-up edge was a contributing factor to the results for the various cutting fluids not being absolutely repeatable in every respect as is evident from the cutting force - and temperature vs. time graphs, (see Appendix D) and to a lesser degree from Table 8.1 and Table 8.3 where the influence of the built-up edge has been avoided as far as possible.

For analysis of the other parameters (i.e. other than cutting force and temperature) during the cutting process, the region of the chip before the sudden decrease in cutting force and the maximum temperature are used, in other words the first quarter of the chip. In this way the unpredictable influence of the built-up edge may be avoided. Despite the built-up edge a high degree of repeatability is attained in the tests for the various cutting fluids, in that the general shape of the graphical results for cutting force and temperature is very repeatable. (see Appendix D).

In Table 8.1 the following parameters were determined from the graphical results:
- the average peak cutting force
- the average peak temperature prior to formation of the built-up edge
- the average of the 5 point moving average of the cutting force at formation of the built-up edge
- the average distance cut to formation of the built-up edge
- the average temperature at the quarter fraction of length of cut

The order in which the results are presented is dry, carbon tetra-chloride, the alkanes, the esters and lastly a poly-isobutylene formulation. The alkanes are paraffin or common illuminating paraffin, a heavier alkane fraction formulation referred to as C or SC and a light alkane fraction displayed or referred to as sample D (SD or D) in the results. The three ester formulations are also referred to as P8, SA and SE and the poly-isobutylene as SB or PIB.

Lubricant	**Peak Cutting Force (N) (Average of 5 tests) + 1**	**Peak average Temperature (°C) prior to BUE formation 2**	**5 pt. MA Cutting force (N) prior to BUE formation 1**	**Average distance (mm) cut to formation of BUE ** 2**	**Temperature (°C) at quarter fraction of length cut 2**	**Smooth fraction on chip 2**	**Chip thickness ratio**
Dry	494 **7**	312 ±4 **3**	324, 323±3 **1**	69, 72±14 **4**	304 **8**	5/16 **5**	3.66 **8**
CCl_4	490 **5**	333 ±4 **1**	370, 370±2 **7**	89 **2**	296 **2**	4/8 **3**	4.27 **2**
Paraffin	508 **9**	305 **8**	364, 363±6 **4**	100; 95±12 **1**	301 **5**	5/8 **2**	4.27 **2**
Heavier alkane fraction	488, 489±7 **4**	312 ±5 **4**	385, 383±9 **8**	61; 62±6 **6**	307 **9**	2/8 **6**	3.942 **4**
Lighter alkane fraction	503, 502±12 **8**	308 ±7 **5**	366, 372±15 **6**	80; 80±10 **3**	293 **1**	7/10 **1**	4.457 **1**
Ester P8	490 **5**	306 ±4 **7**	350, 350±10 **2**	61; 60±6 **7**	302 **6**	5/16 **4**	3.80 **7**
Ester A	486 **3**	307 ±4 **6**	417, 417±10 **9**	59; 57±5 **8**	302 **7**	2/8 **6**	3.58 **9**
Ester E	484, 481±27 **2**	304 ±11 **9**	365, 364±8 **5**	49; 49±3 **9**	301 **4**	2/8 **6**	3.942 **4**
PIB	482, 479±11 **1**	315 ±4 **2**	354, 358±14 **3**	66; 63±6 **5**	299 **3**	2/8 **6**	3.87 **6**

Table 8.1 Comparison of results for different cutting fluids used.

\+ Average of the peak cutting force adapted to a 200mg chip with the assumption of linearity as the region around 200mg is small
**Top figure indicates average and bottom figure indicates mean and range.

Lubricant	Average length cut (mm) to first break 2	Average chip hardness (HV25) 2	Shear strain per Average chip hardness 2	Chip shear strain (dimension-less) 1	Shear plane angle (°) 1	Repeatability of chip mass (mg)	Approximate Flow zone thickness ** (μm)	Overall per-formance ranking
Dry	62 9	119 9	0.031 9	3.717 8	15.67 2	196±2	20 16	6.22
CCl_4	154 2	109 4	0.039 2	4.29 2	13.45 7	198±1	20 13	2.94
Paraffin	156 1	114 6	0.038 4	4.29 2	13.45 7	197±4	18 5	4.22
Heavier alkane fraction	74 7	115 8	0.035 6	3.98 4	14.57 5	207±2 * 198	10 12	6.28
Lighter alkane fraction	147 3	114 6	0.039 2	4.47 1	12.90 9	198.5±2.5	15 28	3.67
Ester P8	87 4	90 1	0.043 1	3.848 7	15.10 3	201±2	15 14	4.28
Ester A	87 4	104 2	0.035 6	3.646 9	16.0 1	197±2	20-30 3	5.55
Ester E	65 8	108 3	0.037 5	3.98 4	14.57 5	197±4	18 22	5.78
PIB	79 6	113 5	0.035 6	3.912 6	14.84 4	193.5±3.5	10 26	4.44

Table 8.1 continued Comparison of results for different cutting fluids used.

* Data from a separate repeatibility test with no other data logging, and 198mg is the average chip mass from the test chips

** First measurement before BUE region and second measurement in BUE region

Ranking the cutting fluids

The bold numbers in Table 8.1 rank the cutting fluids according to the parameter that is investigated on a scale of 1 to 9, where 1 is most desirable and 9 is least desirable for the particular parameter. The bold numbers in the centre at the top of the columns are the weight of importance of the parameter.

Multiplying the weight factor by the rank and adding the values for all the parameters used for the weighing and dividing by the sum of the weight factors gives the overall performance rating for the cutting fluid. This is summarised in the following formula:

$$OPR = \sum_{i=1}^{n} \omega_i \cdot rank_i \ / \ \sum_{i=1}^{n} \omega_i \qquad \text{Eqn 8.1}$$

Where OPR is the overall performance rating
ω_i is the weight of the i-th parameter
$rank_i$ is the rank of the i-th parameter

The chip shear strain and chip thickness ratio parameter could be ranked the other way round as a smaller chip shear strain may be more desirable, argued from the viewpoint that less chip shear strain means less metal deformation and less metal deformation means less energy needed to perform the cut, but this is not done because chip shear strain on its own without chip hardness data can be misleading.

For example a small chip shear strain is more desirable, consequently because CCl_4 has the second largest chip shear strain it is the second worst cutting fluid.?? Compare the energy for performing the cuts for the different cutting fluids given in Table 8.2, and compare the chip shear strain from Table 8.1.

	CCl_4	**% of Total Energy**	**P8**	**% of Total Energy**	**SC**	**% of Total Energy**
Work on rake face	4.51J	19	5.08J	21.2	4.88J	20.6
Work on shear plane	18.84J	81	18.84J	78.8	18.77J	79.4
Total work	23.35J		23.92J		23.65J	

Table 8.2 Average of the work done in cutting the aluminium plate for 0.375 seconds at 0.133m/s and 0.25mm deep.

Calculating the energy of the work on the shear plane and the work on the rake face and the combined energy to cut the aluminium plate for 0.375 seconds (Eqn 2.7 and eqn. 2.11) yields the results as shown in Table 8.2. In all three cases the distribution of the results before calculating the averages was very narrow showing that the data is very repeatable. Five tests were used for each cutting fluid. The energy involved at the junction between the tool and the work-piece was not taken into account for the total work in Table 8.2.

Cutting process parameter interpretation
Some of the parameters listed in Table 8.1 require further explanation:

- The **peak average temperature prior to built-up edge formation**: This gives an indication of the cutting fluids ability to reduce metal to metal affinity and thereby to prevent metal to metal seizure and to delay or prevent the formation of a built-up edge. The higher this temperature the better.

- The **5 point moving average of the cutting force prior to built-up edge formation** has potential to give an indication of how long the welded zone is i.e. it attempts to show the extent of metal to metal seizure prior to the forming of a built-up edge.

- The **average distance cut until the built-up edge forms** is also an indication of the cutting fluids ability to defer or prevent metal to metal seizure. The longer this distance the better.

- The **temperature at the quarter way mark of the length of cut** is an indication of how quickly the cutting tool heats up. The lower this temperature the longer the cutting time should be before the tool becomes too hot. The lower this parameter the better.

  The temperature at the quarter way mark is an attempt at obtaining an indication of the length of the contact-zone, it tries to show to what extent seizure has taken place relative to another cutting fluid. As far as the temperature determination at the quarter way mark of the cut is concerned (see also the motivation for choice of parameters, under the experimental planning section), for determining the different parameters. It would be more meaningful if the volume of the flow-zone directly above the welded-zone/contact length would be determined at that stage of the cut. It is possible that the intensity of shearing metal atoms over metal atoms in the flow-zone varies from one cutting fluid to another. This is because of a variation of the electronegativity of its constituent atoms and because of the variation of the number of electronegative atoms that adhere to the nascent metal at the cutting edge, thereby weakening the metallic bond. Comparing the volume of the flow-zone above the welded region is therefore incomplete if the ease of chip formation is not taken into account.

- The **smooth fraction** on the underside of the chip shows how long it takes until stick-slip develops. Stick-slip is the result of small welded regions that form and break loose again. The larger this fraction the better the ability of the cutting fluid to prevent welding.

- The **chip thickness ratio** is useful for the calculation of shear plane angle, chip shear strain and the work involved in performing the cut. It also changes when the cutting conditions change suddenly as they do when a built-up edge forms.

- The **average length cut until the chip breaks for the first time** is also an indication of how well a cutting fluid can promote ease of metal deformation. The chip will break in compression due to it having no more plastic capacity. A chip is strained more when a built-up edge forms and it often breaks suddenly when a built-up edge forms. The longer the length of cut the better the ability of the cutting fluid to prevent built-up edge formation and the better the ability to promote ease of metal deformation.

- The **average chip hardness** indicates the ability of the cutting fluid to prevent strain hardening. If the chip is softer then more metal should be cut before the tool becomes worn out. This should promote up-time and save on tool costs.

- **Chip shear strain per average chip hardness** is a measure of how easily chip flow/deformation can take place. If the metal can deform more and exhibit less work hardening then it should be easier to cut. This should enhance tool life and promote up-time or production rate. The greater the value for this parameter the better.

- The **chip shear strain** is used to calculate the previous parameter and indicates the same as the chip thickness ratio.

- The **shear plane angle** is used to calculate the energy used when a cut is made. The energy necessary to perform a cut follows a more or less parabola shaped function. The closer to 0°, and the closer to 90° the shear plane angle the more work is done on the shear plane and also in total. The minimum amount of work needed is at a shear plane angle somewhere in between, and the angle decreases for the minimum when the contact length increases. The minimum however also increases. The cutting fluid can influence the amount of work that is done in total. (see Table 8.2)

- The **repeatability of chip mass** is recorded for control purposes and because it may well be that tolerances are more closely attainable for cutting fluids that exhibit a high degree of repeatability.

- A thicker **flow-zone** shows either hotter cutting conditions, due to a longer welded zone, or greater ease of metal deformation or both. This parameter actually requires the length of contact so that the flow-zone volume may be calculated. The smaller this volume the better, as less metal over metal shearing will occur and therefore less heat will be generated, which will promote tool life.

- The other parameters that were monitored although not shown in Table 8.1 were **surface roughness** (Table 8.3) and **chip shape** (figure 8.7). Chip shape includes the visual observation of the **chip radius**. A sudden decrease in the chip radius is an indication that the effective rake face angle changed as it does when a built-up edge forms.

- **Surface roughness** shows the ability of the cutting fluid to produce a smooth finish. A smooth finish will require less secondary machining time to attain the required end finish and this will increase the production rate as it decreases the production time. A cost savings is thus realised for a cutting fluid that can produce a smoother surface finish.

The readings in Table 8.3 are the minimum readings measured in microns (μm) that were obtained from experiment 6 when measuring the R_a value at a cut-off length of 0.8 and over a length of 13mm at various cuts for the different cutting fluids. The width of these cuts was measured to be 50 microns and by searching for the minimum readings possible on the work-piece in the length wise direction it was taken that the alignment of the Taylor Hobson Surtronic 3P profilometer was such that a measurement would be made in the same groove and not across two grooves. (For more detail on the method see Appendix C, Experiment 6.)

		Dry	Ester 8	Paraffin	Ester A	PIB	Heavy alkane	Light alkane	Ester E
Start	Across	1.28	1.41	1.34	1.36	1.46	1.35	1.31	1.41
	Length wise	0.14	0.13	0.13	0.12	0.12	0.14	0.12	0.13
Middle	Across	1.46	1.41	1.32	1.39	1.40	1.36	1.40	1.39
	Length wise	0.14	0.12	0.11	0.10	0.10	0.11	0.06	0.11
End	Across	1.28	1.41	1.37	1.42	1.38	1.39	1.35	1.38
	Length wise	0.12	0.14	0.12	0.14	0.12	0.12	0.11	0.13

Table 8.3 Comparison of surface roughness values measured in microns for different cutting fluids used.

It was found that the length-wise measurements, i.e. the measurements made in the direction of the cut, are more repeatable than the measurements made across the cuts.
Again, as for the longest smooth distance on the underside of the chip (Table 8.1), the non-polar compounds i.e. the alkanes and paraffin appear to render the smoother overall surface finish the exception being the heavy alkane, that in Table 8.1 also did not have a large smooth fraction on the underside of the chip. Table 8.3 shows that the difference in the minimum surface roughness values varies little for the different cutting fluids, the range being from 1.28 microns to 1.46 microns for the transverse measurements and 0.06 microns to 0.14 microns for the longitudinal measurements.

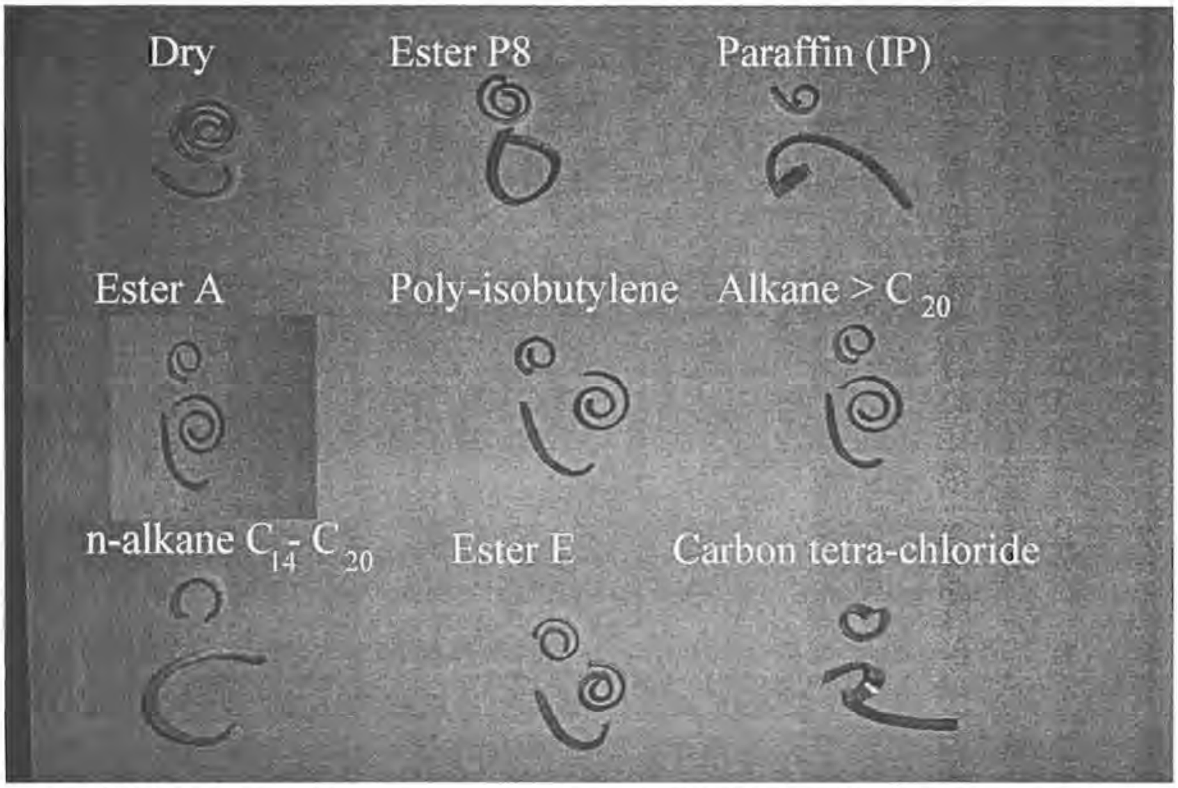

Figure 8.7 Most commonly observed chip shapes for the cutting fluids indicated

For paraffin, the lighter alkane, namely the n-alkane, and carbon tetra-chloride the longer chip is the first chip produced from the cut. Only ester P8 ranks higher in the ease of chip flow parameter of Table 8.1, than these cutting fluids. It is obvious that the decrease in chip radius occurs later for these three cutting fluids than for the other cutting fluids, where the first chip produced in those cuts is the most open shaped chip. This chip is comma shaped for Ester E, the heavier alkane, the PIB, Ester A and the dry cut. Once the effective rake face angle becomes more negative as it does for the built-up edge the chip is curled more tightly, i.e. the chip radius decreases significantly. With ester P8 a built-up edge forms more or less at the same length of cut as for the other esters. Ester A and ester P8 showed both the chip forms given, i.e. the chips of ester A sometimes also looked like those of ester P8 and vice versa. Because these chips are the softest of all the chips (Table 8.1) they have a longer length of cut to first break than ester E. They also display a longer length of cut to formation of the built-up edge.

CCl_4

From literature it is known that CCl_4 is a good metal working lubricant and that it is toxic and therefore cannot be used as a cutting fluid in industrial cutting.(Trent, 1977),(Boston 1952). It is a volatile low viscosity fluid. A molecule of CCl_4 is much smaller than the molecules of most cutting fluids that are used. It consists of five atoms only. In tests done by Trent at low cutting speed namely 8m/min. CCl_4 produced a smoother surface finish than either water or air. The reason for CCl_4 being a good cutting fluid probably lies in the fact that it has i) a small molecule ii) is rich in electronegative atoms and iii) is volatile, thereby aiding evaporative cooling in addition to convective cooling. The high concentration of electronegative atoms at the cutting edge helps to weaken the metallic bond.

When the results (Table 8.1 and Appendix D) from the tests on the shaper are viewed it becomes apparent that the cutting force for CCl_4 is generally somewhat higher than for the dry cut. It is emphasised again that comparisons must be done for data points that lie vertically above each other on the graphs. Furthermore the cutting temperature is also generally somewhat higher than for the dry cut and it could therefore easily happen that the incorrect conclusion is drawn: namely that CCl_4 is not a good cutting fluid because both the cutting force and the temperature are higher which should result in increased operating costs and reduced tool life. The way to actually interpret these results is once again to look at the **non built-up edge region** of the graph. Now in this region the operating temperature is generally slightly lower for CCl_4 than for the dry cut once the quarter way mark of the length of cut has almost been attained, although not much difference is seen between the cutting forces for the same region. In the first five cuts the maximum temperature is reached at a later stage than for the dry cut and the sudden decrease in the cutting force is also at a later time. This shows that CCl_4 is able to resist metal to metal seizure for longer than the dry cut and that the length of the welded-zone in the non built-up region for CCl_4 is shorter. It is therefore clear that CCl_4 is able to decrease metal to metal affinity. It is also clear that the lubricant applicator malfunctioned in test 6, because the built-up edge formed at the same time as for the dry cut. This was already shown and discussed for figure 8.5. In the first column of graphs for CCl_4 graphs 2 to 4 show a 5 pt. moving average in addition to the raw data as presented in all other graphs in the first column.

The next enlightening bit of information about CCl_4 as a cutting fluid is found in Table 8.1. The third best performance in terms of the smooth fraction on the underside of the chip determined as an average for the tests is found for CCl4. Interestingly enough there seems to be a correlation between smooth distance cut and length to first break for which CCl_4 fares second best. It also, together with paraffin, shows the second highest chip shear strain. In the continuation of Table 8.1 in the column for chip shear strain per average chip hardness CCl_4 also fares second best. It produces the fifth hardest chip of the cutting fluids tested. The dry cuts fare poorest, the chips are the hardest and the ease of chip flow is the lowest.

As far as the temperature at the quarter way mark is concerned CCl_4 once again fares second best at 296°C. The maximum temperature of 333°C at which the built-up edge forms is the highest for CCl_4 from which it follows that CCl_4 has the best ability to prevent metal to metal seizure or put another way, to reduce metal to metal affinity. It is therefore expected that CCl_4 will show one of the longer distances of cut before formation of the built-up edge, and it does. CCl_4 has the second longest distance to formation of the built-up edge. CCl_4 produced the most repeatable chip masses. As far as chip shape is concerned CCl_4 was one of two cutting fluids tested that was sometimes able to produce a single contiuous chip over the full length of cut (see figure 8.7). The other cutting fluid was the light alkane (SD). The overall performance rating for CCl_4 is 2.94 and this is also the best of all the cutting fluids that were tested.

Alkanes: (Paraffin, SC, SD)

The next analysis of cutting fluids is that of the alkanes and they are treated as a group. See appendix D for the results of paraffin. Looking at the graphs in columns two and three it is clear that the applicator worked in each test that was conducted, because the vertical difference in cutting force and temperature data points is not almost zero. The heaviest chip seen in test 4 produced the highest peak cutting force.

The cutting force for paraffin is also generally somewhat higher than for the dry cuts. The cutting temperature for paraffin in the non built-up edge region graphs 1 to 5 is also somewhat higher for paraffin than for dry cutting. It is inferred that there is a longer contact-zone for paraffin than for dry cutting as the flow-zone thickness is close to the same; for dry cutting it is 18 μm compared to 20 μm for paraffin, therefore for the same same contact-zone length the cutting temperatures should have been close to the same. The forming of the built-up edge is delayed longer with paraffin than for dry cutting. This is especially clear from the graphs for tests 1 and 2. In graphs 2 and 3 as the built-up edge was forming (slower than for the dry cut) at more or less sample 500 and 540 respectively there is a sudden increase in the cutting force. This is because the built-up edge, or part of it was sheared off. The flow-zone is immediately closer to the dissimilar metal junction of the tool and the chip and the temperature immediately responds. The graphs for paraffin, especially the temperature graphs, have a high degree of repeatability for the non built-up edge region.

- Many more cuts were done with dry cutting than for any other cutting fluid and the fact that built-up edges were sheared off six times in ten runs with paraffin, shows that the built-up edge is weaker when cutting with paraffin than when dry cutting.
- CCl_4 also showed the shearing off of the built up edge namely three times in six tests that were done.
- The shearing off of a built-up edge was far less frequent for dry cutting.
- Paraffin produced the highest peak cutting force for a 200 mg chip: namely 508N compared to the lowest peak of 482N produced for the poly-isobutylene chip.
- The cutting fluid related to paraffin namely the light fraction alkane produced a similar peak cutting force result as paraffin and both of these cutting fluids had a good length of cut to first break, distance cut to formation of built-up edge and a good smooth fraction on the underside of the chip. (See Table 8.1)
- Paraffin for length to first break and length to formation of built-up edge fared best overall and the light fraction alkane third best, but the light fraction alkane fared best for smooth fraction and paraffin fared second best.
- For ease of chip flow the light fraction together with CCl_4 fared second best and paraffin third best.
- The temperatures at the quarter way mark for paraffin and the light fraction alkane are 301 (fourth lowest) and 293°C (lowest) respectively.

For paraffin and the lighter fraction alkane the average peak temperature at the time where the built up edge forms is 305°C and 308°C respectively, which is the same temperature region as for the ester formulations that were tested, but the built-up edge forms later and therefore these temperatures are attained later and the cutting process runs cooler for longer with these cutting fluids than for the esters. This is not pronouncedly so when viewing the graphical results, but the difference is there. It is apparent that the temperature stays higher for longer with paraffin, CCl_4 and the lighter fraction alkane because the built-up edge forms later, and it appears that the initial rate of temperature increase is nearly the same regardless of which cutting fluid is used. If however, the temperatures are compared at regular intervals as the cut develops, the differences are apparent. The quarter way mark temperature comes in useful here. The heavier alkane had the highest temperature at the quarter way mark. It also fared poorly as far as length cut to first break and smooth fraction are concerned. It is in position seven. Together with some other cutting fluids it fares second poorest as far as ease of chip flow is concerned. Only the dry cut fares poorer. Unlike paraffin and its lighter relative, it is not able to delay the formation of the built-up edge for long. The built-up edge sheared off five times in eleven tests. The result for the first test is very similar to the tests where the built-up edge did not prominently shear off and form again.

The quarter-way temperature for this product interestingly is the highest of all the cutting fluids. When the temperature response is compared to the graphs for the dry runs of comparable chip mass in the non built-up edge region the behaviour is similar to that of paraffin and the light fraction alkane in that the temperature is higher than for the dry run. The temperature difference is however less pronounced for the heavier alkane than for paraffin and the lighter alkane. The built-up edge did not shear off and form again when cutting with the light alkane. The shape of the graphical results for the light alkane is the most repeatable of all the results for the cutting fluids that were tested. This once again indicates that the results on the shaper are generally very repeatable.

The shape of the last graphical result for the heavier alkane shows a similar result as for the rest of the tests done for the heavier alkane, but it is clearly noted that the peak temperature and the cutting force are lower over the full duration of the cut because the chip is lighter. Also the amplitude of the oscillation of the cutting force signal decreases when the chip is lighter. This was also shown in figure 8.6.

Based on the results for the light fraction alkane and paraffin it is clear that they perform well as a cutting fluid for aluminium cutting. Their overall performance ratings are 3.67 and 4.22 respectively and these are the second and third best overall ratings (see Table 8.1). The heavier fraction alkane was not able to perform as well as paraffin and the light fraction alkane. The rank it attains for the various cutting process parameters investigated is generally much lower. Its overall performance rating is 6.28 and is the lowest performance rating of all the cutting fluids.

The performance ranking is dependent on the weight that is assigned to the different performance parameters.

Esters: (P8, SA, SE)
The ester cutting fluids that were used generally performed weaker than CCl_4, paraffin and the light fraction alkane.

- The distance cut to first break, the smooth fraction on the underside of the chip and the distance to formation of the built-up edge are markedly shorter.

Looking at the distance cut to first break and the smooth fraction on the underside of the chip ester P8 performs the best when compared to the other esters.

- Ester P8 has the best ease of chip flow of all the cutting fluids that were tested, but the built-up edge unfortunately appears too early.
- In all the tests the esters display a built-up edge that forms earlier than for any other cutting fluids that were tested.
- The esters have a lower peak cutting force for a 200mg chip than the other cutting fluids, probably because they produced the softest chips although in the ease of chip flow SE performed intermediate and SA performed of the second poorest.
- The esters have a lower peak temperature than for the other cutting fluids because the built-up edge forms too early, but it is noted that the quarter way temperature at 302, 302 and 301°C for P8,SA and SE respectively are intermediate and compare well with that of paraffin which is also at 301°C.
- They all display a poor smooth fraction of ¼, except for P8, on the underside of the chip. P8 dispays 5/16, which is only marginally better.
- The esters and PIB typically give two or three chip fragments from one cut whereas one or two fragments result for paraffin, CCl_4 and the light fraction alkane (see figure 8.7).

Poly-isobutylene:

- Poly-isobutylene had the lowest peak cutting force and a slightly better average distance cut to formation of built-up edge than the esters. There was however no correlation found between ease of chip flow and peak cutting force.
- The length cut to first break was more or less the same as seen for the esters.
- The smooth fraction on the underside of the chip was just as poor as for the esters.
- The temperature at the built-up edge was higher, namely 315°C than for the other cutting fluids and if it is taken into consideration that this is at a short distance to formation of built-up edge, the temperature rise is more rapid for this cutting fluid than for the others.
- At the quarter way mark it was third coolest at 299°C.
- When the built-up edge forms it has the second hottest temperature. A question that one may ask is whether this temperature is an indication of the maximum temperature up to which a cutting fluid can withstand built-up edge formation? The answer is probably yes. One problem with PIB is therefore that because this temperature is reached too soon, built-up edge formation happens early: after 66mm of cutting.
- The ease of chip flow is the second poorest.

An explanation to the higher chip thickness ratios when lubricants are used is that the metal grains are able to flow more readily and when the cutting speed is increased the ratios decrease because time to flow decreases and the contact length, or flow-zone length decreases slightly and so the shear in this zone is less. As a result the cutting force decreases, therefore there is less potential for the chip to flow. Another contributing factor is that the tensile strength of the work material is time dependent. This means that it will present stronger when the time over which the force is applied is shortened, but this effect is probably offset by the decrease in tensile strength due to an increase in temperature when the cutting speed is increased. There is a point though, when the cutting speed is increased sufficiently where the temperature in the flow zone increases sufficiently to promote welding of the chip to the tool and then the flowzone length starts to increase again. Severe cratering and tool wear becomes manifest at these speeds. The tool may also break.

Softer materials are more ductile and therefore yield thicker chips. If a cutting fluid is able to better lubricate the metal grains that constitute the work-piece then the chip thickness should increase as lubrication improves. For CCl_4, paraffin and the light fraction alkane good ease of chip flow figures were obtained and the chip shear strains were also high, showing that the chips obtained were thick.

If the cooling effect is dominant over the lubrication as it could be with a high air flow or with cryogenic cutting, then the chip is cooled more intensely than with LVL with a lower air flow, and the material becomes less ductile than it is during dry machining, as a result a thinner chip could be expected.

The results from experiment 4 for the lubricated cuts were presented first with the exception of the hardness tests and the etching work that was done. The results for the hardness tests and the etched micrographs appear on the pages that follow.

Micro-hardness profiles and micrographs

The results for the average hardness were shown in Table 8.1. The micro-hardness test results complemented by optical micrographs were as follows.
All tests were performed using a 25g mass piece on the Vickers Hardness test machine. The first quarter region of the chip was examined in all the tests. This is the region where the underside of the chip is still smooth for all the cutting fluids that were used and no built-up edge was present. All micrographs were at 250X magnification unless otherwise stated.

Cutting dry

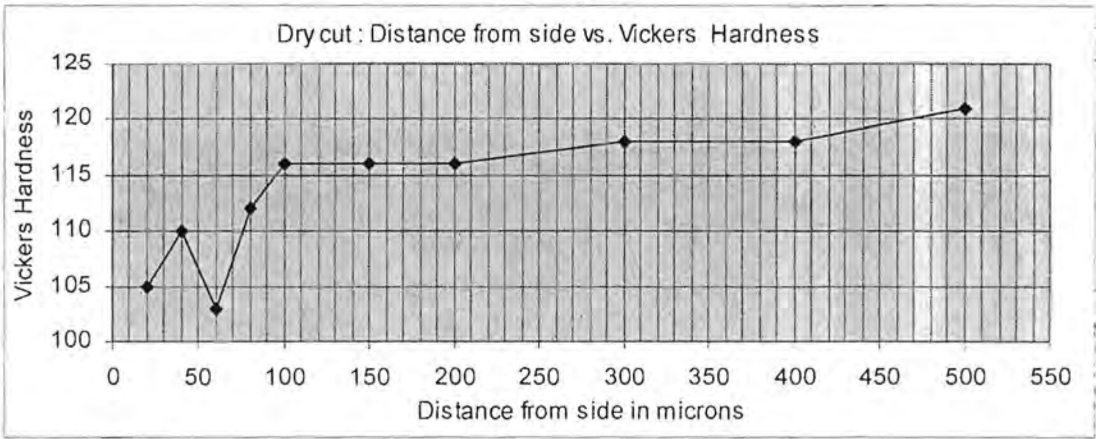

Figure 8.8 Micro hardness profile for the dry cut chip

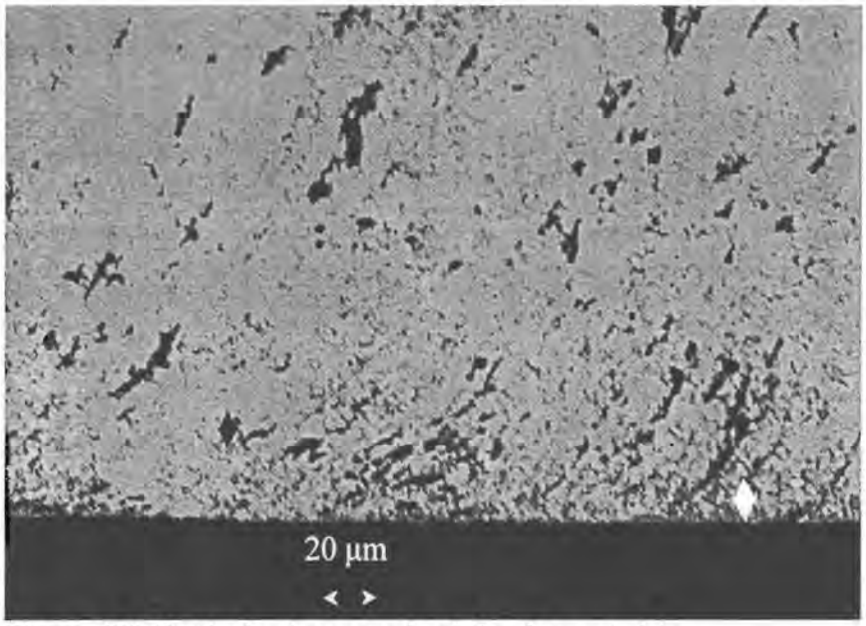

Figure 8.9 Optical micrograph of the dry cut chip

The flow-zone is just less than 20 microns on the micrograph in figure 8.9 and is indicated by the diamond shape. The hardness test prediction (figure 8.8) would have been 20 microns at the most. In all of the following results it will be seen that the chip hardness is fairly uniform and hard in the cold worked region, but when the flow-zone is reached the hardness drops off very steeply because the chip was much hotter in this region and could therefore deform much easier without undergoing severe strain hardening. It is still strain hardened, but less so than in the colder region. Between the cold region and the hot region is a not so clear-cut transition and the hardness in this region sometimes tends to vary slightly. One reason for this could be micro-cracks in the subsurface.

Note how the hardness in the cold worked region differs for each cutting fluid that was used. (See figures 8.8, 8.10, 8.12, 8.14, 8.16, 8.18, 8.20, 8.22, 8.24)

Cutting with Carbon tetra chloride

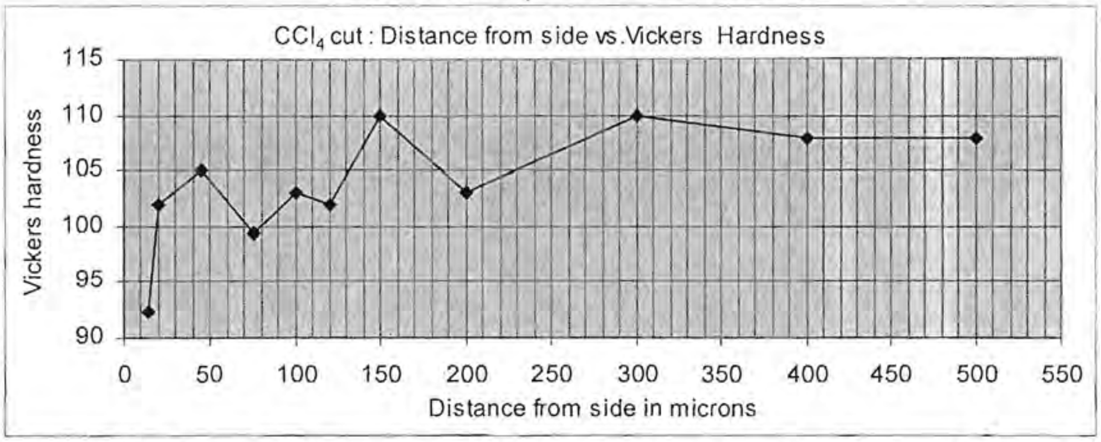

Figure 8.10 Micro hardness profile for the carbon tetra chloride cut chip

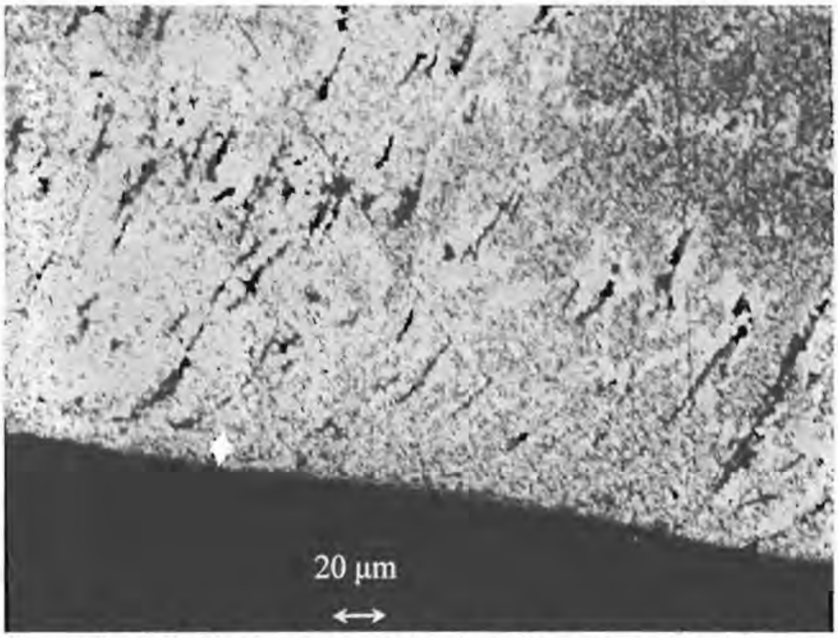

Figure 8.11 Optical micrograph of carbon tetra chloride cut chip

The flow-zone or deformed zone appears at the bottom of the micrograph (figure 8.11) and it is less than 20 microns thick. The diamond shape on the indicates the flow-zone thickness and is used as such on all the micrographs. What is difficult to determine is the point where the flow-zone ends. This is why the micro-hardness test results come in handy so that the flow-zone thickness may be estimated. (figure 8.10) The first data point is at 14 microns from the edge and is definitely in the flow-zone. Its hardness is much less than that of the cold worked region. The second point is at 20 microns. The drop off is very sharp and will be seen again for other hardness graphs. This is why the flow-zone thickness in figure 8.8 was taken as less than 20 microns.

Cutting with Paraffin

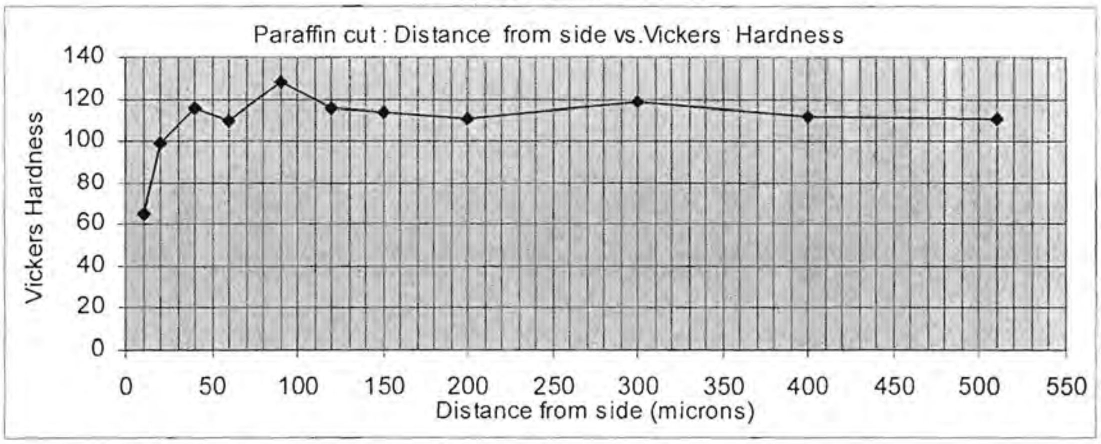

Figure 8.12 Micro hardness profile for the Paraffin cut chip

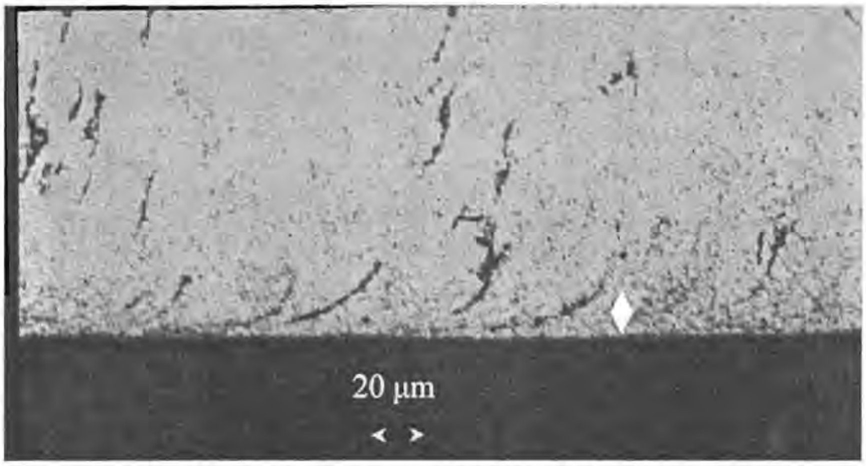

Figure 8.13 Optical micrograph of the Paraffin cut chip

The micrograph (figure 8.13) indicates a flow-zone of slightly less than 20 microns. From the micro-hardness graph (figure 8.12) the flow-zone boundary is taken as close to 20 microns.

Cutting with the heavier alkane

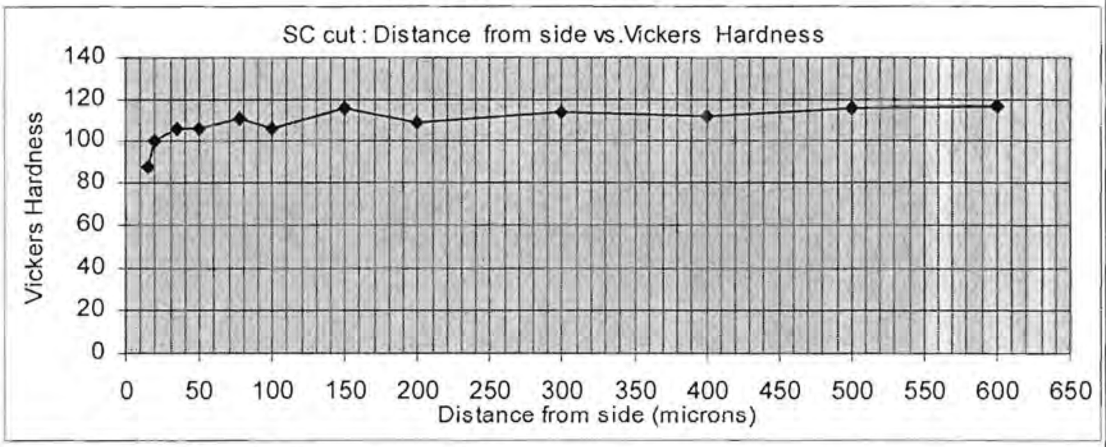

Figure 8.14 Micro-hardness profile for the heavier alkane cut chip

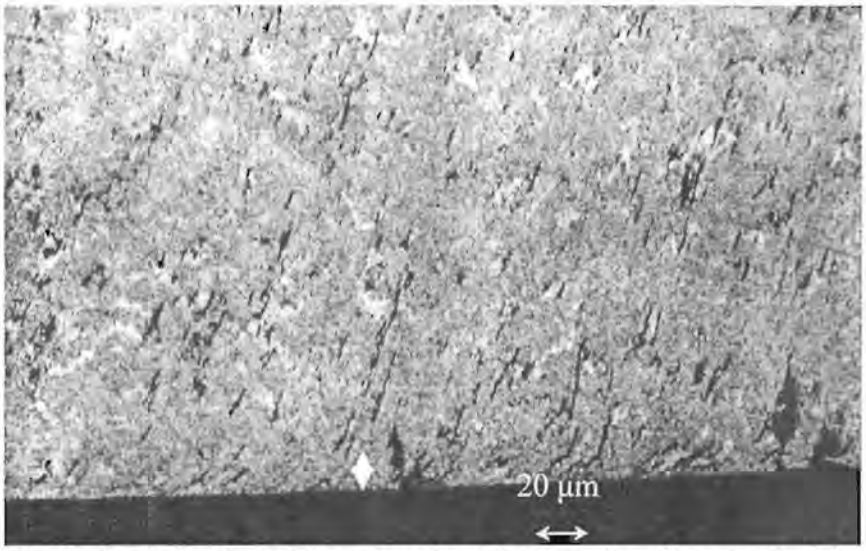

Figure 8.15 Optical Micrograph of the heavier alkane cut chip

The micrograph (figure 8.15) shows a flow-zone thickness of about 15 microns. This estimation is substantiated by the 15 microns that would have been predicted from the hardness test (figure 8.14). The 20 micron is just outside of the flow-zone. This micrograph came out very clearly. The metal in the deformation zone lies more in the horizontal direction slanting up to the right slightly, but outside the flow-zone the metal lies more in the vertical direction slanting a little to the right. This is the case on all the micrographs, only some micrographs are less clear.

Cutting with the light alkane

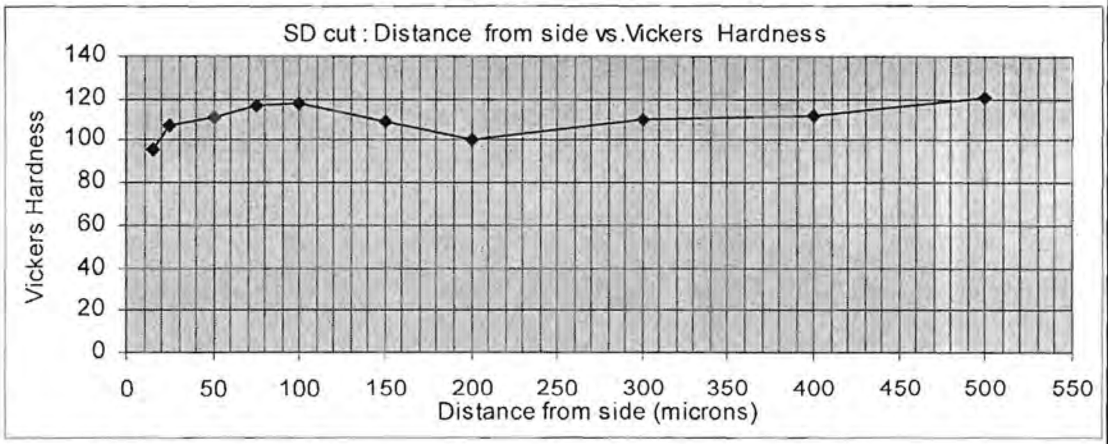

Figure 8.16 Micro-hardness profile for the light alkane cut chip

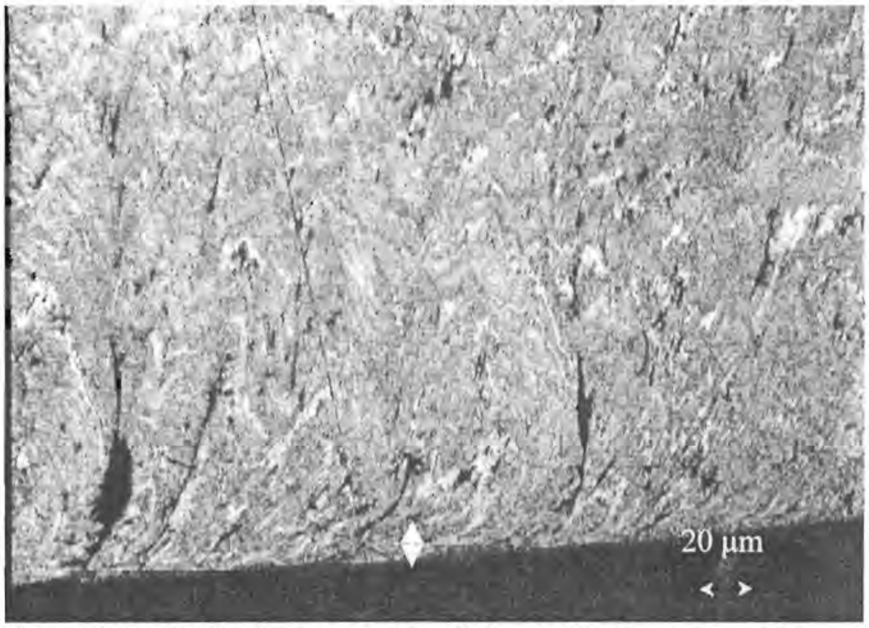

Figure 8.17 Optical micrograph of the light alkane cut chip

The flow-zone thickness from the micrograph (figure 8.17) is about 15 microns. From the hardness test (figure 8.16) it is expected that the flow-zone is close to 15 microns thick. It is clear that the etching process was a success as this micrograph also shows the metal deformation very clearly.

Cutting with Ester P8

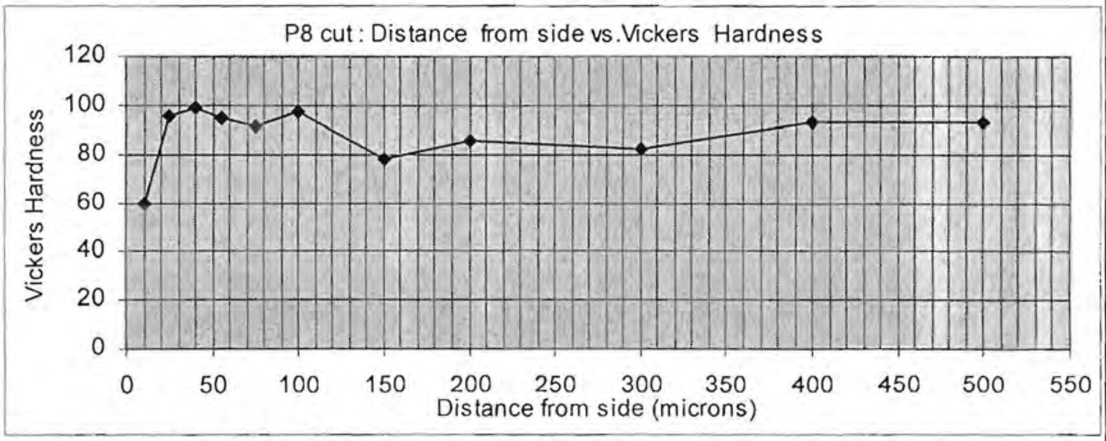

Figure 8.18 Micro hardness profile for the P8 cut chip

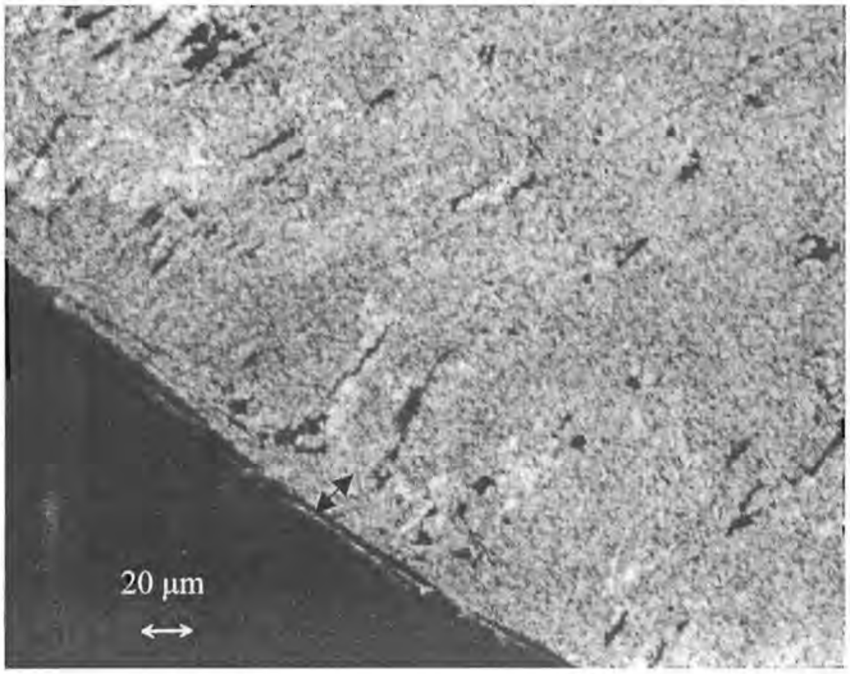

Figure 8.19 Optical micrograph of the P8 cut chip

The flow-zone on the micrograph (figure 8.19)is 10 to 15 microns thick as opposed to less than 25 microns from the hardness test figure 8.18). Another test at 15 microns would have been useful.

Cutting with Ester A

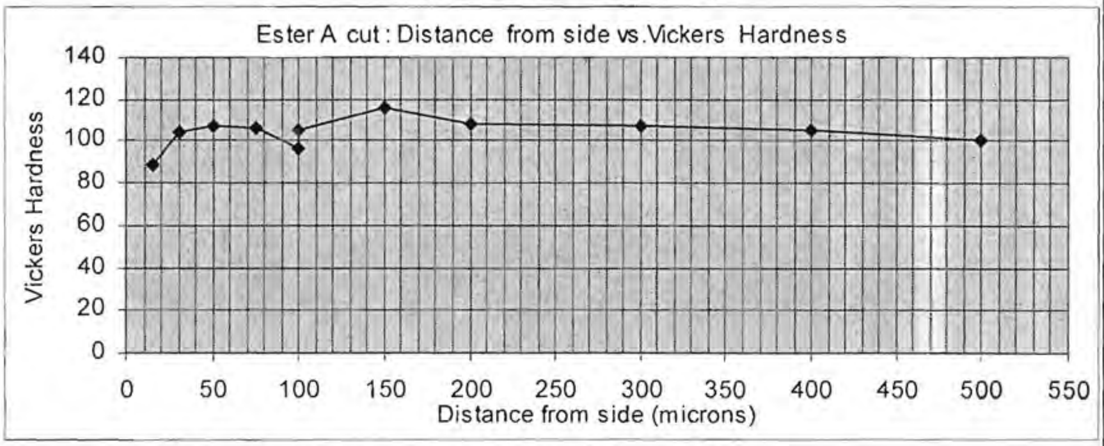

Figure 8.20 Micro hardness profile for the SA cut chip

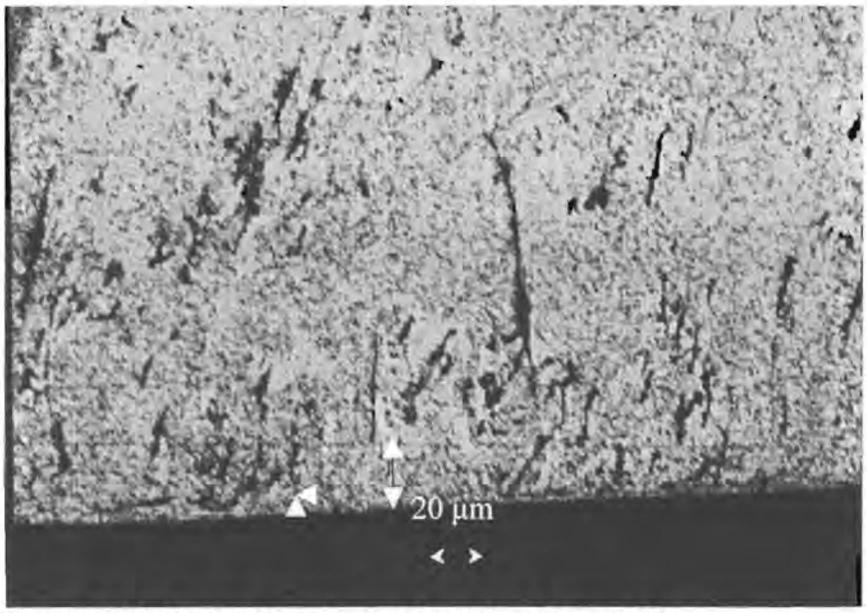

Figure 8.21 Optical micrograph of the SA cut chip

The micrograph (figure 8.21) shows that the flow-zone is between 10 and almost 30 microns thick. It is difficult to determine precisely where the boundary is. The test point at 100 microns appears twice on the hardness graph (figure 8.20). The lower value is for a shot that was placed on a micro-crack in the chip. From the micro-hardness test a little less than 15 microns would have been predicted for the flow-zone thickness. In cases like this one it is very useful to have a micro-hardness profile for the chip.

Cutting with Ester E

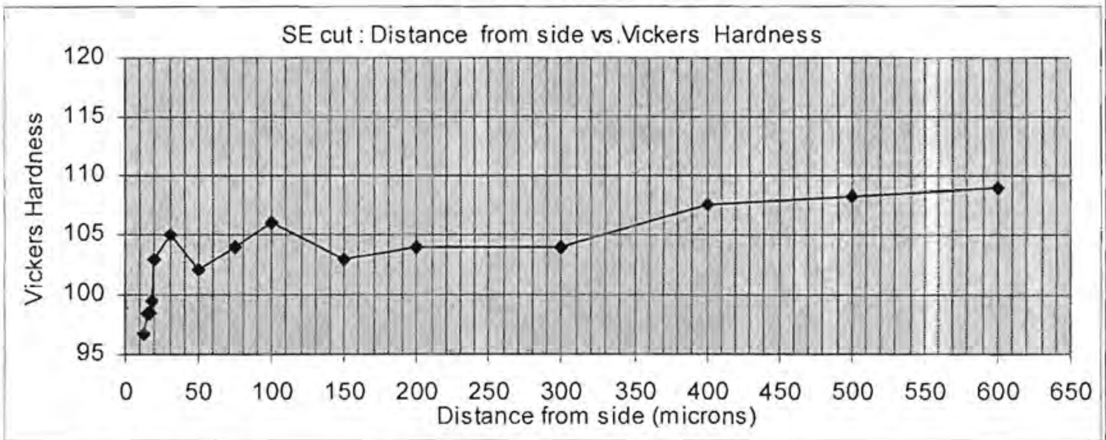

Figure 8.22 Micro-hardness profile for SE cut chip

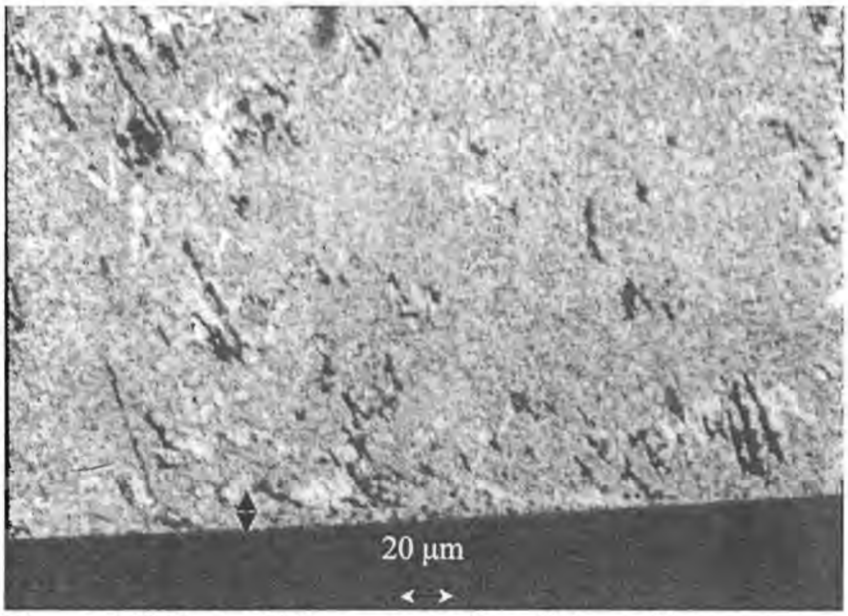

Figure 8.23 Optical Micrograph of the SE cut chip

From the micrograph (figure 8.23) a flow-zone thickness of about 15 microns is expected. The hardness test (figure 8.22) predicts it as 18 microns. This time it can be said with certainty that the flow-zone thickness is 18 microns as many hardness measurements in the immediate vicinity of the flow-zone boundary were made. It is once again apparent how steeply the hardness drops when the flow-zone is entered. Another interesting observation with the chip profiles is that in many cases it is evident that the chip becomes harder as one moves further away from the flow-zone. The reason for this is that the chip is deformed more as it has a tighter chip radius on this side of the chip and is therefore more strain hardened.

Cutting with PIB

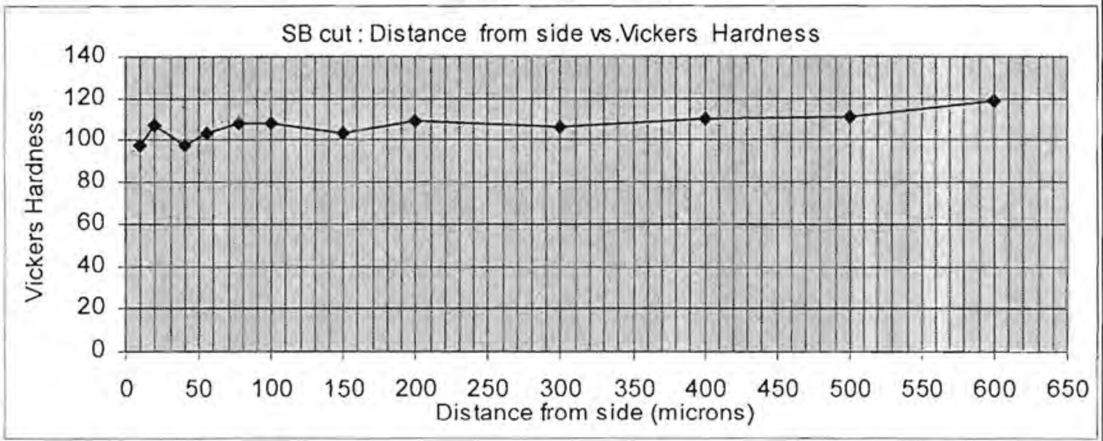

Figure 8.24 Micro-hardness profile for the PIB cut chip

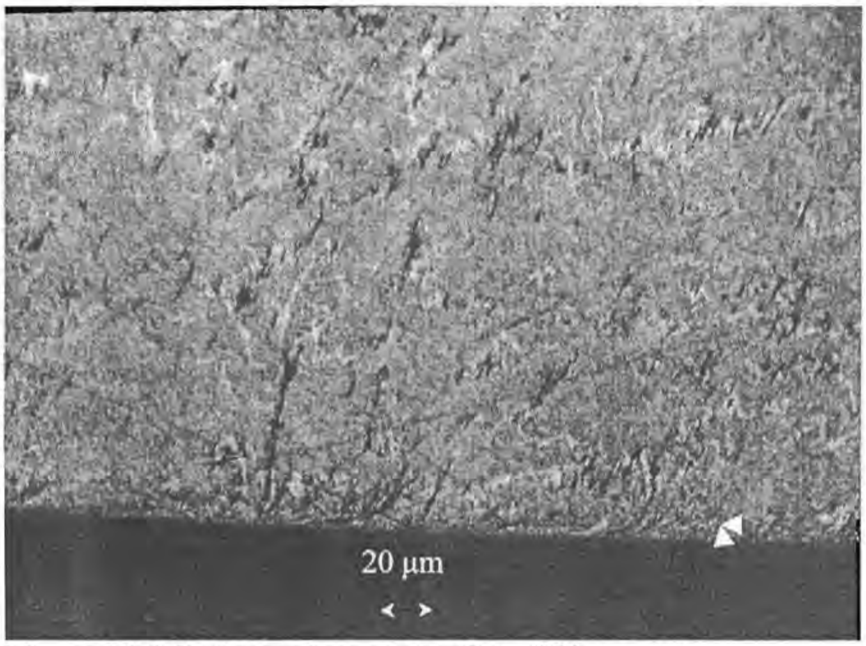

Figure 8.25 Optical micrograph of the PIB cut chip

The micrograph (figure 8.25) shows that the flow-zone is very thin generally less than 10 microns. It is not possible to do a micro-hardness measurement closer than 10 microns from the edge, therefore it is not possible to use the micro-hardness test result (figure 8.24) as a means to verify that the flow-zone is less than 10 microns thick, but it does show that it is not thicker than 13 microns.

The temperature in the non built-up edge region for poly-isobutylene was cooler than the dry cut in 3 of the 5 tests presented. The reason for this is quite likely the fact that the flow-zone is very thin, and as a result less shear is involved.

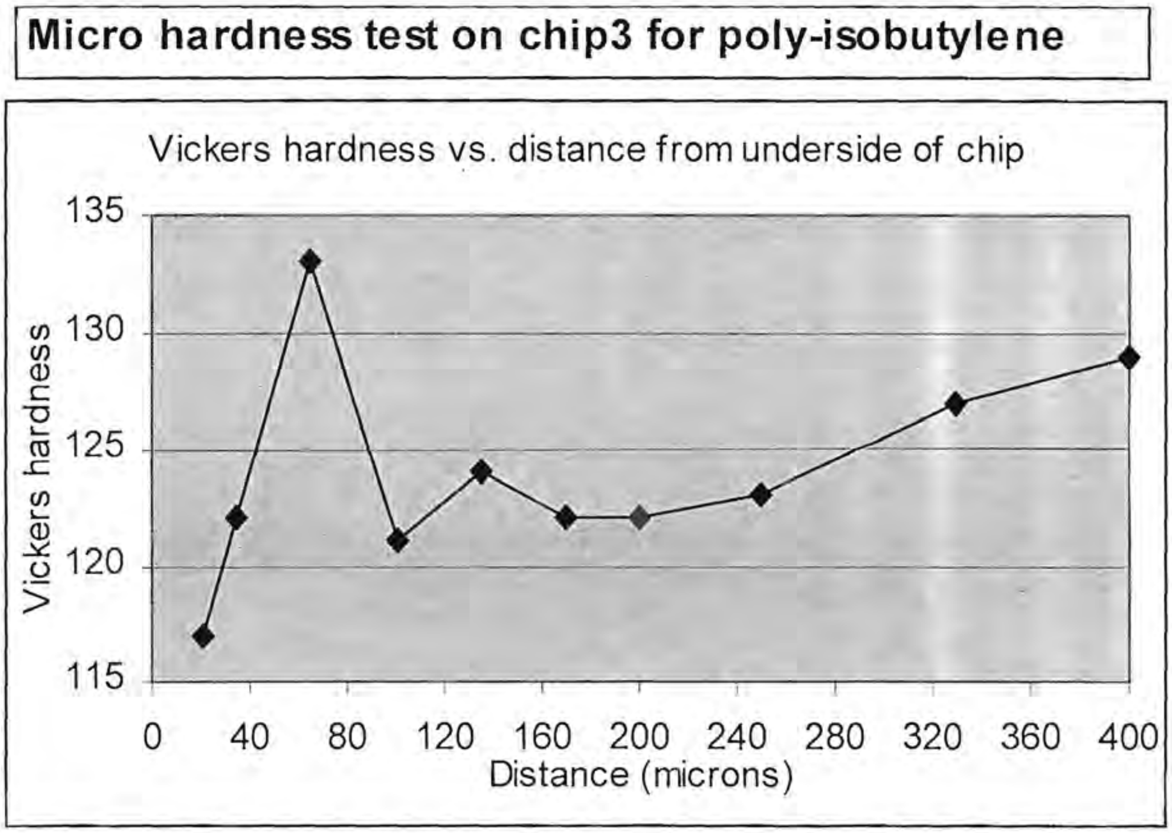

Figure 8.26 The effect of the Built-up edge on the hardness profile of the chip.

The chip becomes significantly harder when a built-up edge is present. It is curled tighter and thereby deformed more thus undergoing severe cold working. From the micro-hardness test depicted in figure 8.26 it appears as if there is a sandwiched layer between the flow-zone and the cold worked region. This high peak hardness is probably the result of the outer part of the chip being colder and therefore more resistant to deformation and on the other side of this peak is a hard tool that harshly pushes against this layer. The outer part of the chip further away from the flow-zone has less bulk that must deform; it can therefore deform easier and probably therefore has a lower chip hardness. As one goes even further away from the flow-zone the chip hardness increases again as a result of a tighter chip radius. The end hardness for SB was 119 before the built-up edge was present (see figure 8.24) after that it is 129. The hardness increases by more than 8 %. The prediction for the thickness of the flow-zone for this hardness profile would be approximately 20 microns. See the SEM micrograph figure 8.27 for comparison.

Generally the thickness of the flow-zone determined from micro-hardness test profiles correlates well with the results obtained from the optical micrographs. It is clear that micro-hardness testing works well to substantiate the results that are obtained from etching and optical micrographs. The two methods are complementary. The third method that was used for the quantification of the flow-zone thickness was to take SEM micrographs.

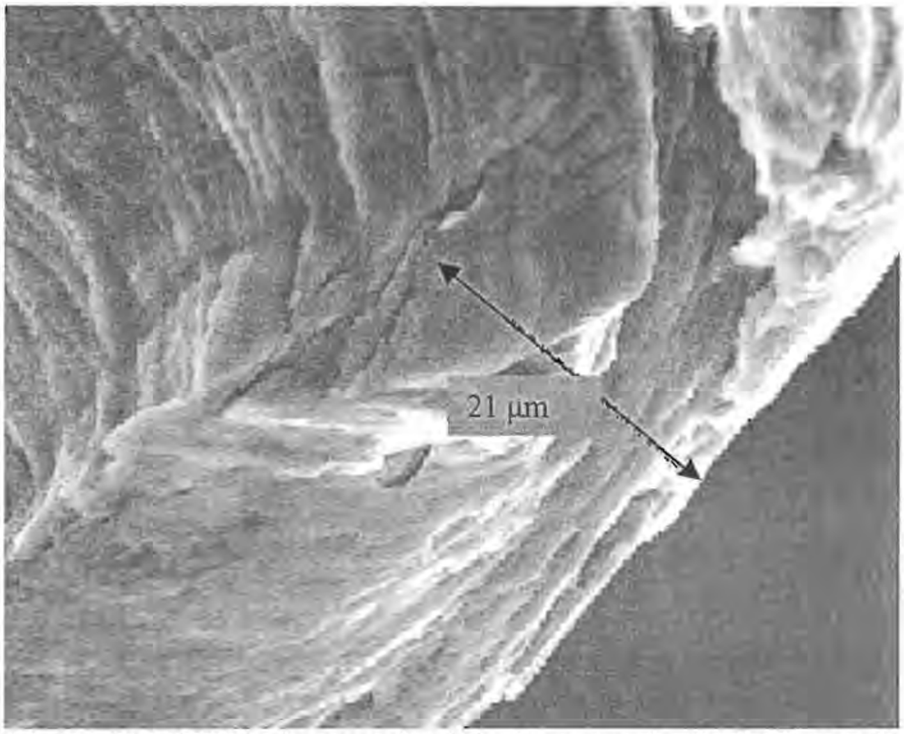

Figure 8.27 SEM micrograph of the flow-zone in the built-up edge region for poly-isobutylene at 2500 X magnification.

The prediction of the flow-zone thickness for this micrograph (figure 8.27) is also close to 20 microns. It once again depends on where the flow-zone will be measured, as the thickness of the flow-zone varies a little with position on the chip. The transition between the flow-zone and the rest of the chip in this micrograph is more clear-cut than on the optical micrographs. Compared to figure 8.22 where a prediction was made based on the hardness profile there is little difference. Both show the thickness as close to 20 microns. This confirms the validity of using SEM micrographs for determining the thickness of the flow-zone.

An indication of what the chip typically looked like at the end of a cut is given in figure 8.28. There was always a little tail at the base of the built-up edge in the chip. SEM micrographs of quick-stop sections would have served well to indicate the length of the welded zone on the rake face of the tool. For this particular chip the length of the flow-zone on top of the built-up edge is about 400 microns. The chip end that is shown is that of Ester P8. It is unlikely that the length of the tail gives an indication of the welded-zone length prior to built-up edge formation as the built-up edge could influence the length of the tail as the cut progresses. The tail does however substantiate that the flow-zone was not in direct contact with the rake face of the cutting tool. The thickness of the tail (figure 8.30) at the point where it departs from the chip is approximately 30 microns, and the thickness of the flow-zone was determined as approximately 15 microns from another SEM micrograph near the end of this chip.

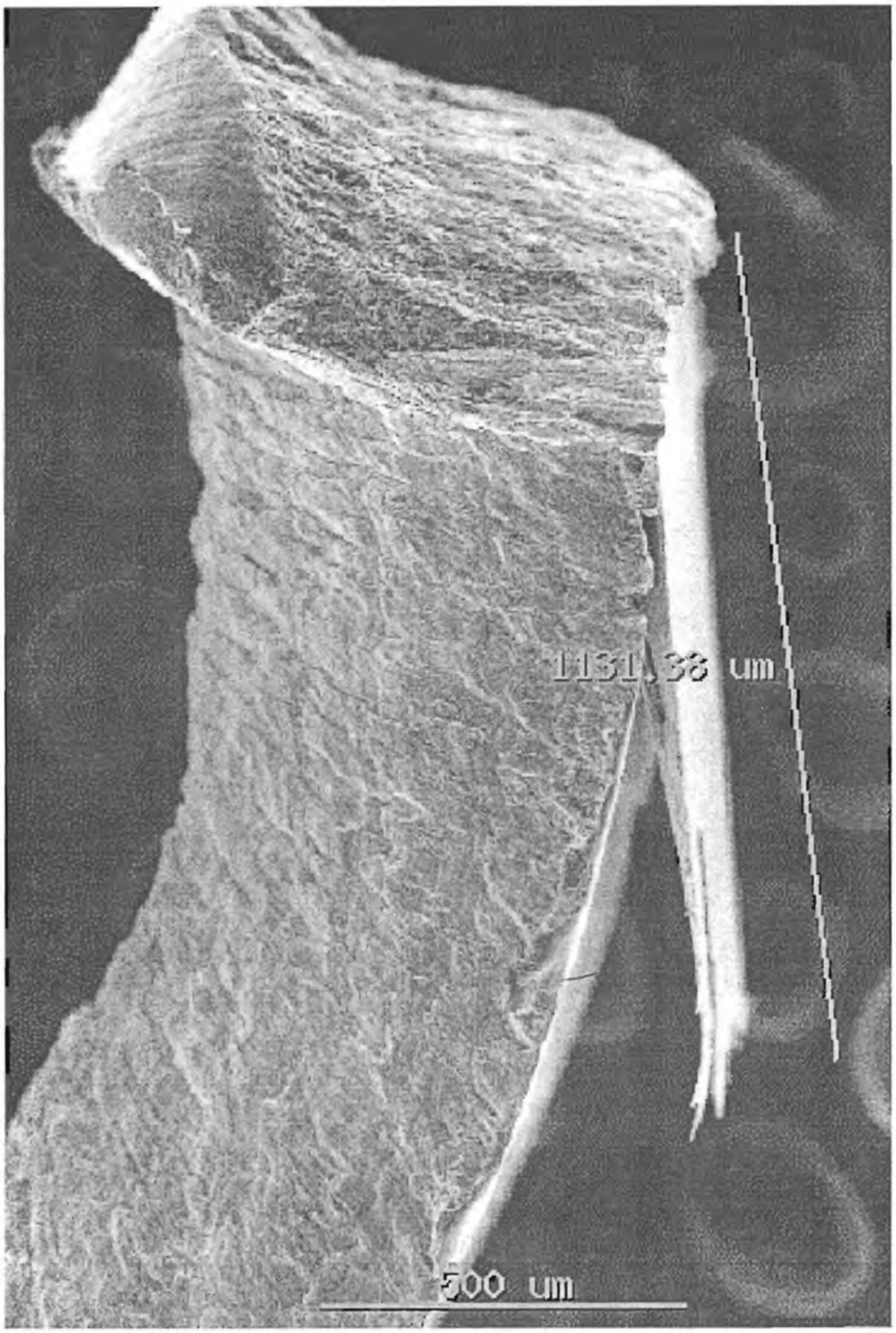

Figure 8.28 SEM micrograph showing a typical chip end at the end of a cut 2500X

From etching and micrography it is substantiated that the built-up edge is present when cutting aluminium. (See figure 8.29)

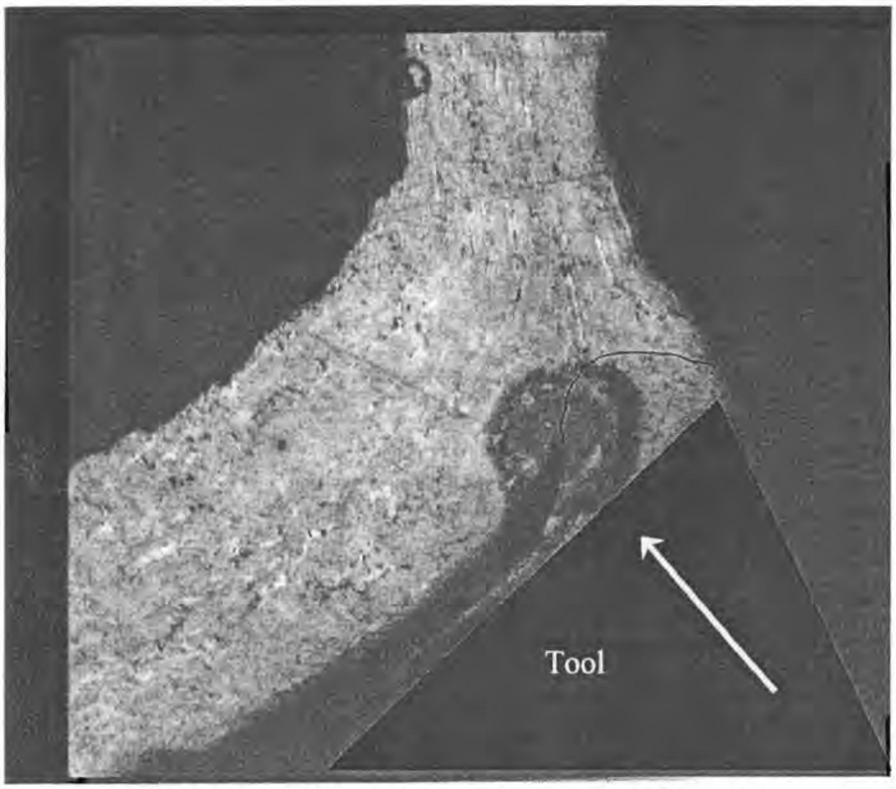

Figure 8.29 Micrograph of the built-up edge obtained when cutting with PIB 125X

It is evident that the chip is much thicker after leaving the tool than when it flows onto the tool. The chip is bent down a little at the part where it was removed from the work-piece. The white arrow on the tool indicates the direction of cut. The built-up edge is not so clearly visible but its boundary has been indicated by means of a black line. The built-up edge is about 400 microns high. The tail part of the built-up edge was originally fused to the rake face of the tool. The dark spot in the middle is where the etchant worked a little too deeply and has nothing to do with the cutting process.

The effect of the built-up edge on the hardness profile of the chip was presented in figure 8.26

For experiment 7 it was found that the cutting force decreases, and the temperature increases with an increase in cutting speed. (See figure 8.30)

Take note of the sampling rate for these experimental results. The time scale may be computed as previously, by dividing the sample number by the sampling rate. The sampling rate is close to 200 Hz in all the experiments.

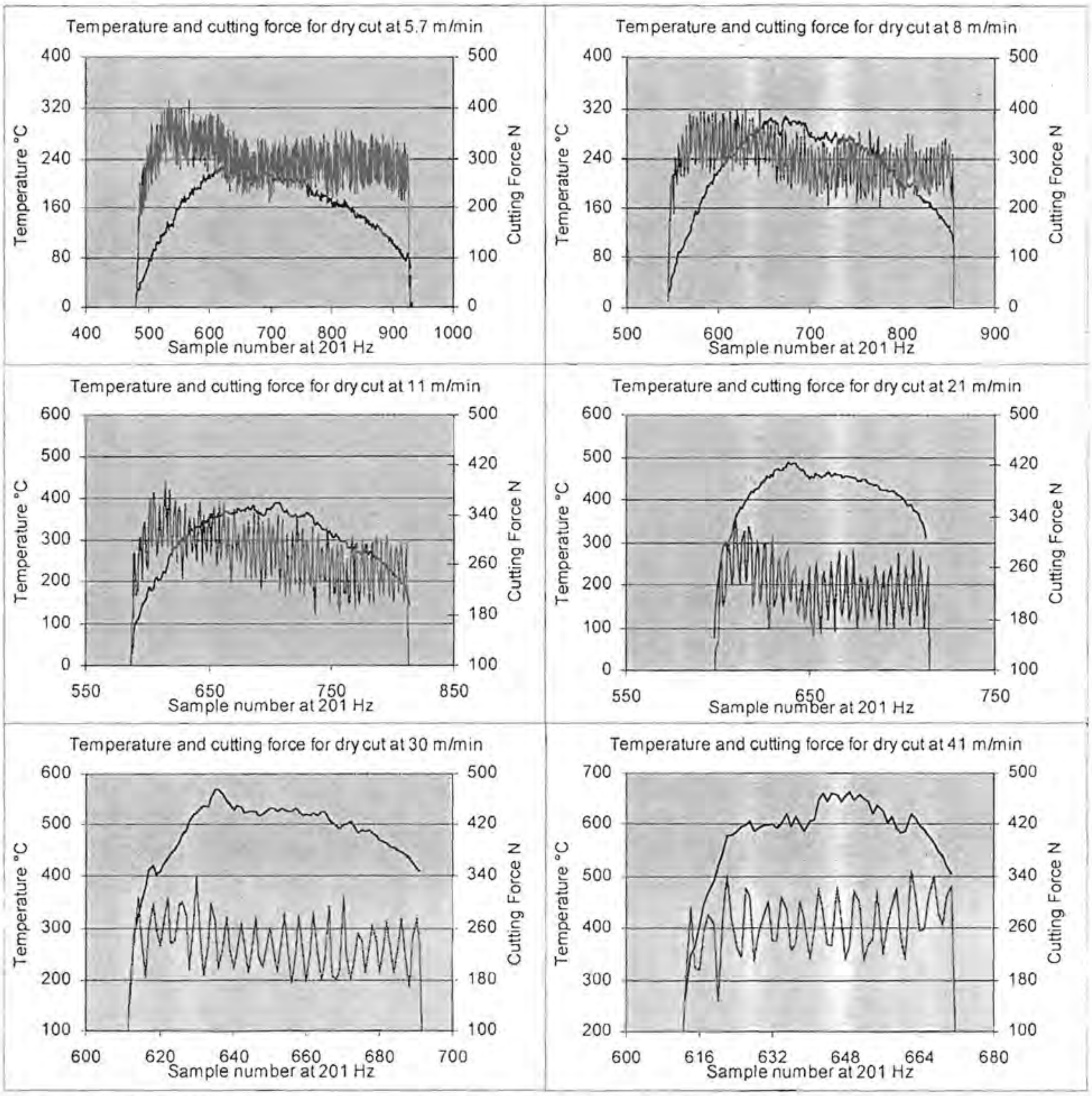

Figure 8.30 Cutting force and temperature response for dry cutting at different cutting speeds

From the graphical results it is clear that the temperature is higher throughout the test with increasing cutting speed. At the higher cutting speeds the cutting force starts to increase again because the built-up edge is being sheared off and thus forms less easily, resulting in a longer welded zone on the rake face of the tool. See also Figure 8.31. At 41 m/min the temperature stays higher for a longer length of cut than any of the other tests done because the built-up edge has the least ease to form at this cutting speed and temperature when compared to the other tests.

When the cutting speed on the shaper is increased to over 60 to 90 m/min. then the built-up edge may or may not occur. This confirms Trent's observations in this regard. (Trent, 1977) (See section 6.1).

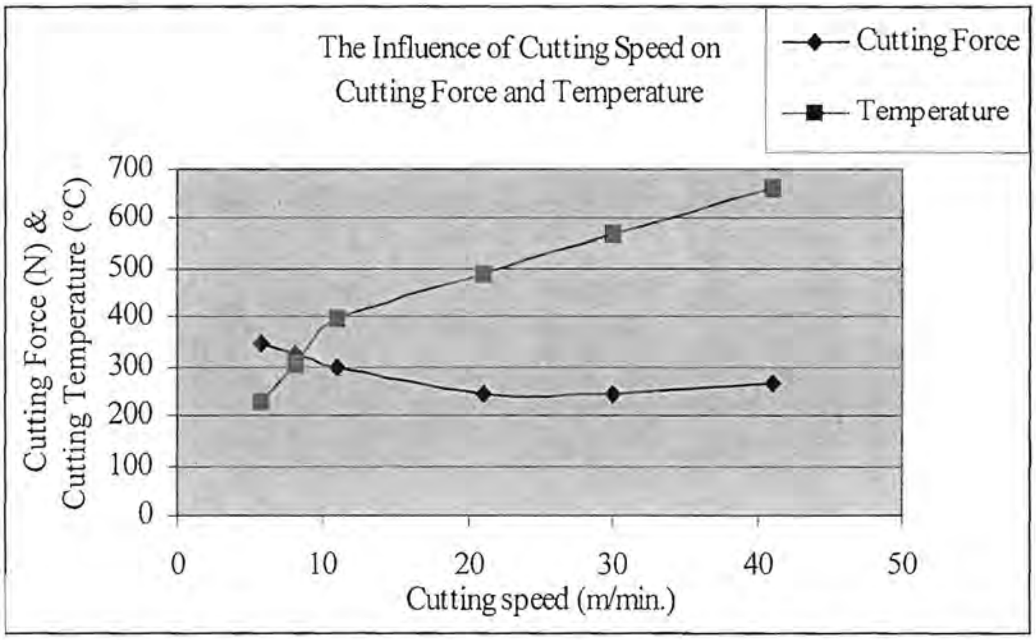

Figure 8.31 The influence of cutting speed on the cutting force and the cutting temperature

9.Conclusions:

The aim of the investigation was to establish a bench test, and to identify parameters that can be measured so that cutting fluid performance during aluminium cutting, when using limited volume lubrication can be evaluated.

1) The results from the tests on the shaper with the tool/workpiece thermocouple set-up and the cutting force measurements show that the test bench serves well for the evaluation of different cutting fluids.
2) The temperature and the cutting force responses are useful in determining when the built-up edge forms, and a micrograph of the etched longitudinal cross section of the chip serves well to substantiate the presence of the built-up edge.
3) The test method is useful for the evaluation of limited volume lubrication cutting fluids, but also has merit for the evaluation of cutting fluids other than limited volume lubrication cutting fluids.
4) The physical measurements of the chips are very useful in distinguishing the various cutting fluids from each other. All other parameters have been kept constant, i.e. the cutting speed and the depth of cut and any other parameters. The only parameter that changes from one test to the next is the cutting fluid that is used; hence **cutting fluids can be compared meaningfully**.

The most important parameters when comparing the different cutting fluids are:
- 1) the smooth fraction on the underside of the chip, this seems to be related to the distance that can be cut until the built-up edge forms
- 2) the distance cut to formation of the built-up edge,
- 3) the chip shape, specifically the chip radius
- 4) the distance cut to first break
- 5) the ease of chip flow,
- 6) the temperature at the quarter way mark at 52mm length of cut,
- 7) the temperature at which the built-up edge forms.

The surface finish obtained in this work was less enlightening as to the performance of the cutting fluids because the difference in surface finish is small, but usually surface finish is also used as a cutting performance parameter. Based on the above parameters CCl_4, the light fraction alkane, paraffin and Ester P8 are the best cutting fluids of the cutting fluids that were tested. One should have tested a product which is **not** a cutting fluid to confirm that surface finish is unacceptable.

Obtaining results such as that CCl4 is a good cutting fluid and that the cutting force decreases and the cutting temperature increases with an increase in cutting speed substantiates that the work done on the shaper can verify the results that are commonly observed during metal cutting.

Tremendous temperature gradients are involved in metal cutting. When a built-up edge forms, the welded-zone length decreases leading to reduced shearing of the metal. The maximum temperature and hence emf that is attained in the cutting process should be found in the flow-zone directly above the welded zone as this is the region of maximum deformation rate. Due to the built-up edge the flow-zone is somewhat removed from the dissimilar metal junction at the interface of the tool rake face and the chip where the thermocouple e.m.f. is generated. Thus it was expected that temperature would decrease significantly when a built-up edge forms and it is exactly what was found from the experiments. The signal that is measured varies as the built-up edge changes. The larger the built-up edge the lower the temperature that is observed.

The built-up edge is undesirable, because if it is sheared off and passes on the underside of the tool, it causes surface defects on the worked material and it contributes to tool wear. If the formation of a built-up edge could be prevented such defects could be avoided, and this can be achieved by increasing cutting speed. The built-up edge is a type of seizure phenomenon. The longer it can be prevented from forming the better the anti-seizure properties of the cutting fluid are, and if cutting speed is increased, then these anti-seizure properties should aid the cutting process by decreasing cutting forces, tool temperatures and wear.

To complement monitoring of the flow-zone, micro-hardness tests may be done on the chip in addition to optical micrography. The hardness tests are also used when the ease of chip flow parameter is calculated. The work-piece material of aluminium was etched with 0.5%HF (hydro flouric acid) in distilled water (van der Voort, 1999). This helps to give an indication of the thickness of the flow-zone and whether a built-up edge was present or not, therefore if the experiment is performed with a quick-stop the length of the welded zone can also be determined by etching and micrographs. The SEM micrograph was also useful in complementing the result from the micro-hardness test. The hardness alone does not quantify whether a cutting fluid has good performance - it is the hardness in combination with the chip shear strain that seems to matter, as the cutting fluids that had the best performance also had good ease of chip flow figures. No parameter should be used on its own to evaluate cutting fluid performance. The full scope of performance parameters should be evaluated before a decision to use a certain cutting fluid is made.

The limitations into an investigation of the chemistry involved are severe, as the conditions that prevail in the contact-zone, (the region of maximum shear-rate and therefore the hottest region in the cutting process) are very harsh and the cutting fluids used are organic compounds with additives. The harsh conditions cause thermal degradation and mechanical breakage of the carbon chains of the cutting fluid. The contact-zone is often a continuous phase as welding between the tool and the work-piece is so complete. The only way that a chemical may penetrate the boundary of this region is by means of small molecules in the gas phase, thereby slightly decreasing the contact-zone area and thus reducing shear which becomes evident in a decrease in the cutting force, the e.m.f. generated and the shorter radius of the chip that is produced by the machining process.

The electronegativity and population density of the electronegative atoms of the cutting fluid seem to play a role in the cutting performance of the cutting fluids. They serve to weaken the metallic bond in the vicinity of the cutting edge. CCl_4 performed the best and has the highest population density of highly electronegative atoms of all the cutting fluids that were tested. A weakening of the metallic bond will also lead to reduced cutting force and cutting temperature. The carbide or nitride coating on many tools helps to protect the tool against seizure to the chip, i.e. the welded zone is shorter, therefore lower cutting temperatures and consequently higher cutting speeds are possible with these tools than with HSS tools. The electronegative atoms of the cutting fluid compete as much or more for the electrons of the work-piece as the carbon and nitrogen atoms of the tool coating, because they have similar or higher electronegativity. The carbon and nitrogen atoms on the tool already hold onto the electrons of the substrate of the tool and therefore have a lower affinity for the electrons of the work-piece. The work-piece electrons are therefore attracted more by the cutting fluid and this demotes the affinity of the cutting tool for the work-piece material.

All tests were compared to dry machining for the same tool and work-material combination, and the temperature from the tool/work-piece thermocouple and the cutting force were monitored for different cutting fluids. The significant change in cutting force and temperature are useful in determining when the built-up edge forms and from this it is seen that some cutting fluids can delay the formation of the built-up edge for longer. The temperature and the distance cut at which the built-up edge forms are an indication of the ability of the cutting fluids ability to prevent metal-to-metal seizure.

When using limited volume lubrication for metal cutting it is important that the correct cutting fluid is found for the tool and work-piece combination of metals, as this influences the success of the metal cutting operation.

Metal cutting is an extremely complex operation. There are many parameters that play a role, and by also quantifying parameters that are not normally measured in an industrial operation it becomes possible to gain more insight on the efficiency of various cutting fluids. Test work in the laboratory can save on a lot of downtime in the industry because cutting fluid evaluation can be done without interfering with the industrial cutting operation.

Limited volume lubrication has a lot of merit in metal cutting in that it is more environmentally friendly than conventional flood type lubrication for metal cutting, requires substantially less cutting fluid, can deliver the same performance or better than flood lubrication by increasing tool life and producing acceptable end finishes on the metal surfaces. It also has merit for producing good finished surfaces in that there is less chance that the finished work-piece surface will be blemished or stained by residual cutting fluid, because very small volumes of cutting fluid are used. This also helps to facilitate ease of chip recovery. As very limited volumes of cutting fluid are used and no recycling of cutting fluid occurs, maintenance of cutting fluids and disposal of used cutting fluids are not issues. All these positive attributes of limited volume lubrication help to promote production up-time.

10. Recommendations:

Now that a test method is available, that can distinguish between different types of cutting fluids, a lot of future work can be done.

All the experiments performed in this investigation took a mechanical approach towards experimentation for the acquisition of data for analysis of the cutting process, and they are definitely necessary for cutting fluid evaluation. More tests on the shaper should be performed, both for a cutting speed where the built-up edge does form **and** for a cutting speed where it does not form.

The cutting fluids should be divided up into the various chemical families and an investigation into the effects of chain length, polarity and steric hindrance of the molecules can be done.

As far as analysis of chemistry involved in metal cutting is concerned, an identification of the types of metal salts that form and of the atoms or molecules that occur on the underside of the chip and on the rake face of the tool can be made. The physical parameters that are measurable to verify good cutting performance have been identified, and an investigation into the type of metal salts and or atoms or molecules on the surfaces should be made. This can be done by MS, SEM or FTIR.

When using limited volume lubrication for metal cutting it is important that the correct cutting fluid is found for the tool and work-piece combination of metals, as this influences the success of the metal cutting operation, therefore limited volume lubrication should not be written off in a hurry as a technology that does not work. It is recommended that the correct cutting fluid is found.