Effect of EDT on Formability of Aluminum Automotive Sheet
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**Introduction**

Novelis is the world leader in aluminum rolling and aluminum recycling. The Novelis Global Technology Centre in Kingston, Ontario, Canada, is a research and development facility that focuses on optimizing aluminum production processes, material characterization and testing. An important part of their research activities is sheet metal forming operations. During these operations the sheets are clamped between a die and a blankholder and due to plastic deformation they change shape, conforming to the shape of the tools. This process is mainly limited by localized necking, shear fracture and wrinkling. Computer models are developed to predict the material behavior during such a process. In order to validate these models, experimental data is necessary. This data can be obtained by performing well-known test, such a tensile tests and hardness tests, but also by generating Forming Limit Diagrams.

This report deals with experimental results from creating Forming Limit Diagrams (FLD). First is explained what a FLD is, how it can be obtained and how it is used in practice. After that, the experimental procedures used are explained. Then results are given from the performed tests. First the formability of different aluminum alloys was tested by creating their FLDs. Not only standard sheet thicknesses like 0.8mm or 1.0 mm, but also can body sheets.

After this, research has been done for the effect of EDT (Electric Discharge Texturing) on Formability of Aluminum Automotive Sheet. In today’s automotive industry there is no consensus regarding this effect. European car manufacturers use EDT treated aluminum sheet for the same applications in which North American producers use mill finish treated aluminum sheet. In spite of this different point of view, the automotive industry has failed to investigate this area of research.

After the results, some problems during testing are discussed. After that conclusions will be given that follow from the performed experiments.
1. Forming Limit Diagram

A very useful and commonly used method of visualizing the limit strains is a Forming Limit Diagram, in which a plot of the Major Strain ($\varepsilon_{11}$) versus the Minor Strain ($\varepsilon_{22}$) at the onset of necking is generated (figure 1). The diagram can be split into two sides; “left side” and “right side”. At the “right side”, which was first introduced by Keeler and Backofen [1], only positive Major and Minor Strains are plotted. Goodwin [2] completed the FLD by adding the “left side”, with positive Major and negative Minor Strains. Various strain paths can be generated in order to create different combinations of limiting Major and Minor Strains. The “left side” represents strain paths with strain ratios ($\rho = \varepsilon_{22}/\varepsilon_{11}$) that vary from uniaxial tension ($\rho = -0.5$) to in-plane plain strain ($\rho = 0$). On the “right side” the strain ratios differ from in-plane plain strain to full biaxial ($\rho = 1$) stretching.

Connecting all of the limit points leads to a Forming Limit Curve (FLC), which splits the “fail” (i.e. above the FLC) and “save” (i.e. below the FLC) regions. But in spite of their common use and time researchers have spent, the accuracy and precision of FLDs are still not satisfying. The scatter in the plot of strain measurements is large. This is not only because of the measuring technique, but also of the material behavior itself. Approximating the FLC is thus a subjective process.
FLDs are used as an indication of the formability of a certain material (i.e. A FLC shifted up or down indicates respectively a better or worse formability). Also FLDs are used in combination with Finite Element Programs (figure 2). As the Major and Minor Strains are known, they can be compared with the FLD if no limit points are exceeded. Because of the large scatter a “safe” FLD is often plotted which is 10% below the actual FLD in order to guarantee no failure in practice.

Usually FLDs are determined by using one of the following two types of test methods. The first one is the Marciniak in-plane test (figure 3) where a sheet metal sample is strained by a flat-bottomed cylindrical punch. Between the punch and the metal sheet is a steel driver with a hole in the centre. This creates a frictionless in-plane deformation of the sheet. In order to generate different strain paths to create the FLD, different sample widths (figure 4) are used. When a big width is used, the external forces that act on the sample are greater than the internal forces, resulting in biaxial stretching. In case a small width is used, high external forces in for example the x-direction cause higher internal forces in y-direction than the external forces in y-direction, resulting in stretching in x-direction and compressing in y-direction.
The other test is the Nakazima (Dome) out-of-plane test (figure 5), which uses a hemispherical punch. Since for this test deformations are not frictionless, lubricants are used. The necessary strain paths are obtained by using different lubricants, creating different friction conditions, and also with different sample widths. Strain paths for the “right side” of the FLD are generated by use of different lubricants, where different widths are used for obtaining strain paths in the “left side” of the FLD.
2. Experimental procedure

For creating the FLDs, only the Marciniak in-plane method has been used. In addition to this, also Limit Dome Height (LDH) tests and standard tensile test have been carried to study the formability effect of the EDT aluminum automotive sheets

2.1. Marciniak test

For the Marciniak in-plane test the aluminum specimens were cut into 200x200 mm. For strain analysis a square grid of 2.77 mm line spacing and 0.23 line thickness was applied on each specimen by a silk screening method. Then in each sample two slots were pierced along the rolling direction at different widths in order to generate the preferred strain paths. The widths used were 60, 100, 115, 120, 125, 130 and 140 mm.

After that a full circular locking bead was pressed into the specimen (picture 6).

Between the punch and the specimen a steel driver of 200x200 mm and 0.75 mm thickness was used. A hole of 42 mm diameter was pierced into the driver the same time as the locking bead was pressed.

The Marciniak in-plane test was performed by a computer controlled hydraulic press (see Appendix A). Specimens were clamped by a circular locking bead with a hold-down pressure of 190 bar. This allowed the specimen only to deform inside the area of the locking bead, because not material can flow from underneath the locking bead. A video camera was mounted directly above the specimen. During testing there is no punch movement, the specimen is being formed over the punch, resulting in a
constant distance between the camera and the specimen throughout the test. This allows pictures to be taken sequentially. Pictures were taken every 5 seconds for the first part of the test and every 0.2 seconds after that until fracture occurred. In general the first part ended after 15 mm crosshead travel. Only for the can body material this method wasn’t used, because fracture occurred much earlier. Therefore during tests for this material for each strain path 2 samples were used. The first one is used to indicate when fracture occurs. During deformation of the second sample the sequence of pictures taken every 0.2 seconds is started manually.

Testing was performed by a crosshead traveling speed of 10 mm/min. The punch was cylindrical, flat bottomed with a diameter of 100 mm and a draw radius of 11.9 mm. In order to have a uniform deformation, Vaseline was applied by hand on the driver surface facing the punch.

During testing the grid is captured and processed automatically using CAMSYS ASAME (Automatic Strain Analysis and Measurement Environment) software. First the grid needs to be calibrated by using an undeformed sheet. Major Strains must be equal or less than 2%, Minor Strains must be equal or greater than –2%.

After testing the images had to be processed. In order to locate the same grid points in every image, the specimens were marked with black spots before testing. The selection was 13x13 grids and located is the middle of the sample. After making a selection, the image is being cropped, cleaned and if needed repaired by connecting missing gridlines. Then the grid is mapped and strain is calculated automatically by the software. A triangular based Lagrangian strain calculation is used and by using Mohr’s circle for plane stress, the definitions for Major and Minor true Strains are:

\[
\varepsilon_{\text{Major}} = \ln\sqrt{1 + 2E_{\text{max}}}
\]

\[
\varepsilon_{\text{Minor}} = \ln\sqrt{1 + 2E_{\text{min}}}
\]

where

\[
E_{\text{max}} = E_{\text{average}} + r
\]

\[
E_{\text{min}} = E_{\text{average}} - r
\]

with

\[
E_{\text{average}} = \frac{E_{11} + E_{22}}{2}
\]

\[
r = \frac{1}{2}\sqrt{(E_{11} - E_{22})^2 + (2E_{12})^2}
\]
The frame closest to failure determined the limit strain. This was close enough as pictures were taken every 0.2 seconds which is every 0.033 mm crosshead travel as the crosshead traveling speed is 10 mm/min.

2.2. Tensile testing

For tensile testing a CNC (Computer Numerical Controlled) milled “dog bone” shaped specimen was used with a gauge length of 50.8 mm and a width of 12.7 mm. They were all cut longitudinal to the rolling direction.

The specimen was placed and gripped automatically and stretched at two different rates. In order to obtain an accurate Young’s Modulus the specimen was stretched at 2.54 mm/min (0.1 inch/min). As the 0.2% offset yield stress was exceeded, a stretch rate of 12.7 mm/min (0.5 inch/min) was used until fracture occurred. Strains were measured by a High Resolution Digital Extensometer (HRDE). Loads were measured by a load cell. Data was collected during stretching at 20 Hz and saved automatically. For each individual test, Young’s Modulus, yield stress, maximum stress, strain hardening exponent, plastic strain ratio and maximum strain was determined.

![Figure 7: Tensile testing machine](image)
2.3. **Limit Dome Height test**

Aluminum specimens for the Limit Dome Height (LDH) out-of-plane test were cut into 190.5x190.5 mm (7x7 inch). They were clamped between an upper and lower die at 250 kN. A full circular lock bead was formed during closing of the dies. A hemispherical punch of 101.6 mm was pressed into each sample at two different speed rates. At first a speed rate of 25.4 mm/min (1 inch/min) was used until a certain point before fracture. This point was roughly estimated and set manually. Stretching after this point was continued at 4.99 mm/min in order to be able to stop the punch quickly after fracture to prevent overshoot. During recording load and punch displacement was recorded. A polyurethane lubricant was used between the punch and the specimen to obtain a uniform deformation. Because of this, the punch displacement does not represent the limit dome height. During deformation of the sample, the lubricant also deforms. To measure the actual limit dome height, the specimens were clamped between the dies again after testing. A calibrated micrometer was then used to measure the actual dome height.

![Figure 8: Machine for performing Limit Dome Height tests](image-url)
3. Graphical representation

As mentioned in Chapter 1 the scatter in a FLD is large. Therefore another representation method had been used. As visualized is figure 9, five lines are drawn perpendicular to the crack. For each line the Major and Minor strain was calculated. This data was then plotted separately versus the distance to the crack. A polynomial was fitted for each line through all the data points. The limit point for the strain path was the average of the 5 maximums of the Major strains and the average of the Minor strain at zero distance from the crack. (figure 10).

Figure 9: Plot of Major Strain at the onset of necking. Five lines were drawn perpendicular to the crack.

Figure 10: Plot of Major and Minor Strain at the onset of necking of five different lines perpendicular to the crack.
Using this procedure resulted in a limit point that was certainly at the location of the crack. Since there is no scatter anymore, an objective method was used to fit the FLD to the measured data. A Matlab program (see Appendix B) was written for performing all these calculations.

When plotting the FLD the fitting procedure was spitted into two sides, the left and right side. Because the left side is mostly a straight line and the right isn’t, fitting all the data in one time would not be a good representation of the FLD (figure 11). Therefore the straight line is extrapolated until it crosses the Major Strain axis. This point is then used to fit also the right side of the FLD data points (figure 12).

Figure 11: False fitting of data points as a representation of a Forming Limit Curve

Figure 12: Correct fitting of data points as a representation of a Forming Limit Curve
4. Results

4.1. Standard Aluminum sheets

The used material for this experiment are displayed in table 1:

<table>
<thead>
<tr>
<th>Material</th>
<th>Coil Number</th>
<th>Gauge height [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X626-T4PB</td>
<td>H08837</td>
<td>1.21</td>
</tr>
<tr>
<td>X626-T4PB</td>
<td>H21613</td>
<td>1.01</td>
</tr>
<tr>
<td>X613-T4PD</td>
<td>H16139</td>
<td>0.905</td>
</tr>
</tbody>
</table>

The nomenclature of the material is based on the aluminum alloy (e.g. X626 or X613) and the heat treatment process (e.g. T4PB or T4PD). The temper designation T4 means the solution is heat treated and naturally aged by the user to a substantial stable condition. The Forming Limit Diagrams of the tested materials are given in figure 13.

The “left side” is equal for all the alloys. But the “right side” differs a lot for the X613 material in comparison to the X626 material. The in-plane plain strain, also known as FLD₀, is for all the alloys almost the same.
4.2. Can body

Can body material is characterized by it’s thickness of 0.3 mm or less. The material used was 3104 with a thickness of 0.269 mm and a H19 temper which means it has been cold-worked to give the material a different tensile strength. In figure 14 results form the Marciniak test a displayed.

![Figure 14: FLD of can body material](image)

The limit strains are much smaller than with standard sheet thicknesses. When clamping the sample, the sheet changes shape a little, which can be observed by different reflection of the light. This is thought to be no plastic deformation, but the limit strains are too small to guarantee this completely. The fracture lines are located at the borders of where the shape changes were noticeable. If the limit strains were bigger, the initial effect would vanish, since the deformation is much larger.

During testing there were some indications of false test conditions. When pressing the lock bead into the sheet, there was a lot of wrinkling outside the lock bead area. To check if there actually was any plastic deformation, the ASAME software could not be used, because the software is calibrated after the sheet has been clamped and therefore a lock bead is needed. A sheet was clamped an unclamped and analyzed with the IBAS software. This software uses a video camera which captures the grid on the sheet. To calibrate the system a ruler has to be placed on the sample. An original sheet was also measured. Then the data was plotted using FLD analysis software. The outcome was that there was when pressing the lock bead into the sample there is no plastic deformation.
4.3. **EDT Automotive Aluminum Sheet**

The available material was AA6016 with a T4 temper and gauge height of 1.16 mm. A Comparison was made between a standard mill finish treated surface and two different EDT production routes, named Standard EDT and Mini-Mill EDT (figure 15). Electric Discharge Texturing is a well-known machining process, where energy of electric discharges are used to remove material from the surface. The textured surface is produced by a bank of electrodes which are moved along the roll surface as the roll is rotated. Electrode positioners ensure that each electrode is properly spaced with respect to the workpiece, to ensure that the electrode is close enough to the workpiece to create a texturing spark through the dielectric fluid, but not too close to create a current flow without generating any sparks.

The difference between the two production routes was that the Mini-Mill EDT textured surface used a smaller roll diameter, than that was used in Standard EDT texturing. Also the Mini-Mill EDT surface was reduced by 2-3% during the final pass where the standard EDT had a thickness reduction of 4-5%.

![Figure 15: Mill Finish (left), Standard EDT (middle) and Mini-Mill EDT (right)](image-url)
For the tensile test, 13 individual tests of each surface have been carried out. In figure 16 the averaged result is given. During testing, only displacement and load data was collected. Therefore to determine the true stress and true strain the following definitions have been used.

\[
\varepsilon_{\text{True}} = \ln\left(1 + \varepsilon_{\text{Engineering}}\right)
\]
\[
\sigma_{\text{True}} = \sigma_{\text{Engineering}} \left(1 + \varepsilon_{\text{Engineering}}\right)
\]

Where

\[
\varepsilon_{\text{Engineering}} = \frac{\text{Displacement}}{\text{Gauge length}}
\]
\[
\sigma_{\text{Engineering}} = \frac{\text{Load}}{\text{Cross section}}
\]

The Young’s Modulus of the material used is approximately 72 Mpa for all surface treatments. Also the yield stress of all the surface treatments can be found close to each other at around 123 Mpa as well as the strain work hardening exponent, which is about 0.265. Conclusively it can be stated that there is no significant difference between a Mill Finished surface or an EDT treated surface for uniaxial stretching.
Results from the Marciniak in-plane tests are given in figure 17. The curves do not fit each other completely, but these findings, however, can be interpreted as measurement errors, since the difference in Major Strain is only 2 to 3\%.

Despite the difference, there was no indication of a formability effect of the EDT for in-plane stretching.

![Figure 17: FLDs from Automotive Aluminum sheet](image)
From the data obtained during the Limit Dome Height test, the highest and lowest values were discarded. The mean value of the remaining data was determined and plotted in figure 18.

For the Mill Finished surface the Limit Dome Height was on average 32.06 mm whereas the LDH for the Standard EDT treated surface was on average 36.14 mm. This is a significant indication of a formability difference between an EDT treated surface and a Mill Finished surface for an out-of plane deformation. This difference is less noticeable between the Mini-Mill EDT treated surface and the Mill Finished surface.

![Figure 18: Results from Limit Dome Height test for Automotive Aluminum Sheet](image-url)
5. Encountered problems

The first encountered problem was a difficulty throughout the test. For creating a FLD, different widths are used to generate the different strain paths. Some of these strain paths contribute in a more important way to the overall shape of the FLD than others. These strain paths usually are 60, 115, 120 and 140 mm. With most of the tested materials, generating the 120 mm strain path appeared to be very difficult if not impossible when experimenting with the used setup.

Normally the fracture was located in the middle of the sample, only when using the 120 mm strain path, fracture occurred most of the time at the radius of the sample. Since strains can only be measured in the middle of the specimen because of in-plane conditions, measured strains did not represent limit strains if the fracture was at the radius of the sample. Though these strains could be used as an indication, because the limit strains were almost reached, they could not be plotted in a FLD as being limit strains.

A reason for this problem could be that the friction conditions were not completely uniform. There could be more friction at the side where fracture occurred than on the other side. But applying more Vaseline on the driver surface facing the punch, didn’t solve the problem for the 120 mm width. Although it most of the times did when the 125 mm width generated the same problems.

Another possible reason could be, that the punch is not completely horizontal, creating more pressure at one side. Or the one of the dies is not properly aligned. Normally this would not be noticed, but maybe for the 120 mm width having a completely horizontal punch because very critical. Unfortunately this could not be measured, because there was no space using measuring instruments between the dies. The whole machine had to be taken a part, but this was not possible.

Another problem occurred during measurements with the EDT treated sheets. Although the 120 mm width could not be used as all, also the widths of 125 mm and more didn’t generate limit strains. Problem was, that the maximum machine displacement was not enough for the sheets to fracture.
The punch needed to be higher, but a new punch was not an option. So a new bottom plate was milled, which was 15 mm higher than the original one. After installing the new bottom plate, the sheets could not be loaded properly anymore, because when the clamps were open, the top of the punch was still higher than the lower die. Solution was to raise the initial position of the clamps when they were opened. Do to this is was needed to know how machine and operating files worked. After studying all these files, the machine coding was known and the initial position could be changed into the desired height.

After this problem was solved, another problem occurred. Since the displacement was bigger, the hole in the driver became bigger as well. If 130 mm or 140 mm widths were used, some sheets showed fracture at the radius at several points. Reason for this was, that the hole of the driver had reached the radius of the punch and started to fracture, causing a fracture in the sheet as well.

Using a smaller diameter hole, caused the driver to fracture even earlier. A bigger hole could be a solution, but simply drilling was not an option because this was not precise enough. Changing the tools that punched the hole and the lock bead into the driver was not an option as well, because whole new tooling had to be milled and this was not possible.
6. Conclusion

Experiments have been carried out to create Forming Limit Diagrams of different aluminum alloys. Because in a normal FLD the scatter is large, creating a Forming Limit Curve is a subjective process. Therefore a different graphical representation method was used, which resulted in an objective method of generating FLCs. The standard aluminum sheet materials tested were X626-T4PB with a thickness of 1,016 mm and 1,21 mm and X613-T4PD with a thickness of 0,905 mm. Little difference was noticeable for the “left side” of the FLD for all the alloys. At the “right side” however, the FLC of the X613-T4PD alloy was significant lower. Therefore it can be concluded that the formability of the X613-T4PD material is worse than the X626-T4PB material.

Also can body sheets have been tested. The used alloy was 3104 with a thickness of 0.269 mm and a H19 temper. The generated FLD appeared to be reliable, but the clamping method is possibly pre-deforming the sheets. Results were therefore maybe incorrect or not constant. In order to create FLDs for can body material another clamping method has to be used, which doesn’t effect the initial state of the sheets.

Generating all the FLDs of these aluminum alloys was more a general introduction of how Forming Limit Diagrams are created. The most important research was to study the effect of EDT Automotive Aluminum Sheet on formability. Therefore three different tests have been carried out. In-plane Marciniak tests and tensile tests did not reveal any significant difference in formability. As expected the surface area only contributes for a small part in the total deformation. Material defect within the sheet have a much great influence. For out-of-plane LDH tests however, a significant difference could clearly be distinguished. The lubricant acted differently on the Mill Finished surface in comparison to the EDT treated surface. This led to different friction conditions resulting in higher dome heights for the EDT treated surface. Also, since for out-of-plane deformation the strain gradient in the surface is of greater influence than for in-plane deformation, surface treatments will have an effect on the formability.
No difference was detected for in-plane deformation because it was frictionless, however, for out-of-plane deformation a clear effect was visible. It can therefore generally be stated that an EDT treated surface has a positive effect on sheets formability.

Only one type of lubricant was used, because of limited available sheets. It is recommended more types of lubricants can be used, to study the effect of surface treatments for out-of-plane in more detail.
Acknowledgements

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References


Appendix A

Machines necessary for experiments

Slot piercing machine

Lock Bead pressing machine

Marciniak testing equipment

Marciniak testing machine
Appendix B

Matlab program

clear all
close all
cle

nn = 6;
% situation 1 = horizontal crack
% situation 2 = any other crack orientation
situation = 1;

%________________________________________________
% Selection of elements on lines
nodes1 = [25 40 50 71 102 116 133 148 164];
nodes2 = [22 37 53 58 84 100 115 130 146];
nodes3 = [35 50 66 81 97 112 128 143 159];
nodes4 = [32 47 63 78 94 110 125 140 156];
nodes5 = [61 76 92 107 123 138 154 179];
crack = [69 98];
%
% Importing data from ASAME Software

data1=importdata('MF60_1.xls');
data2=importdata('MF60_2.xls');

[m,n]=size(data1);
data1(:,2)=data1(:,2)-data1(m,2);
data1(:,3)=data1(:,3)-data1(m,3);
rown1 = nodes1+1;
rown2 = nodes2+1;
rown3 = nodes3+1;
rown4 = nodes4+1;
rown5 = nodes5+1;

%________________________________________________
% Making equation of crack to calculate perpendicular distance form node to crack

xel = (data1(data2(crack(1)+1,2)+1,2)+data1(data2(crack(1)+1,3)+1,2))/2;
ylel = (data1(data2(crack(1)+1,2)+1,2)+data1(data2(crack(1)+1,3)+1,2))/2;

xe2 = (data1(data2(crack(2)+1,2)+1,2)+data1(data2(crack(2)+1,3)+1,2))/2;
ye2 = (data1(data2(crack(2)+1,2)+1,2)+data1(data2(crack(2)+1,3)+1,2))/2;
a = (ye2-ylel)/(xe2-xel);
b = yel;
% Extracting Major and Minor Strain from data

Major1 = data1(rown1,5);
Minor1 = data1(rown1,6);
Major2 = data1(rown2,5);
Minor2 = data1(rown2,6);
Major3 = data1(rown3,5);
Minor3 = data1(rown3,6);
Major4 = data1(rown4,5);
Minor4 = data1(rown4,6);
Major5 = data1(rown5,5);
Minor5 = data1(rown5,6);

% Extracting the coordinates of the selected elements

xn1 = data1(rown1,2);
xn2 = data1(rown2,2);
xn3 = data1(rown3,2);
xn4 = data1(rown4,2);
xn5 = data1(rown5,2);

yn1 = data1(rown1,3);
yn2 = data1(rown2,3);
yn3 = data1(rown3,3);
yn4 = data1(rown4,3);
yn5 = data1(rown5,3);

% Calculating distance perpendicular to crack by making two linear equations

xsolvn1 = (yn1+(1/a)*xn1-b)/(a+1/a);
ysolvn1 = a*xsolvn1+b;

xsolvn2 = (yn2+(1/a)*xn2-b)/(a+1/a);
ysolvn2 = a*xsolvn2+b;

xsolvn3 = (yn3+(1/a)*xn3-b)/(a+1/a);
ysolvn3 = a*xsolvn3+b;

xsolvn4 = (yn4+(1/a)*xn4-b)/(a+1/a);
ysolvn4 = a*xsolvn4+b;

xsolvn5 = (yn5+(1/a)*xn5-b)/(a+1/a);
ysolvn5 = a*xsolvn5+b;

if situation == 1;
    for i = 1:length(xn1)
        if yn1(i) < ysolvn1(i);
            distn1(i,:) = sqrt((xn1(i)-xsolvn1(i))^2+(yn1(i)-ysolvn1(i))^2);
        else
            distn1(i,:) = sqrt((xn1(i)-xsolvn1(i))^2+(yn1(i)-ysolvn1(i))^2);
        end
    end
end
for i = 1:length(xn2)
    if yn2(i) < ysolvn2(i);
        distn2(i,:) = -sqrt((xn2(i)-xsolvn2(i))^2+(yn2(i)-ysolvn2(i))^2);
    else
        distn2(i,:) = sqrt((xn2(i)-xsolvn2(i))^2+(yn2(i)-ysolvn2(i))^2);
    end
end
for i = 1:length(xn3)
    if yn3(i) < ysolvn3(i);
        distn3(i,:) = -sqrt((xn3(i)-xsolvn3(i))^2+(yn3(i)-ysolvn3(i))^2);
    else
        distn3(i,:) = sqrt((xn3(i)-xsolvn3(i))^2+(yn3(i)-ysolvn3(i))^2);
    end
end
for i = 1:length(xn4)
    if yn4(i) < ysolvn4(i);
        distn4(i,:) = -sqrt((xn4(i)-xsolvn4(i))^2+(yn4(i)-ysolvn4(i))^2);
    else
        distn4(i,:) = sqrt((xn4(i)-xsolvn4(i))^2+(yn4(i)-ysolvn4(i))^2);
    end
end
for i = 1:length(xn5)
    if yn5(i) < ysolvn5(i);
        distn5(i,:) = -sqrt((xn5(i)-xsolvn5(i))^2+(yn5(i)-ysolvn5(i))^2);
    else
        distn5(i,:) = sqrt((xn5(i)-xsolvn5(i))^2+(yn5(i)-ysolvn5(i))^2);
    end
end
if situation == 2;
    for i = 1:length(xn1)
        if xn1(i) < xsolvn1(i);
            distn1(i) = -sqrt((xn1(i)-xsolvn1(i))^2+(yn1(i)-ysolvn1(i))^2);
        else
            distn1(i) = sqrt((xn1(i)-xsolvn1(i))^2+(yn1(i)-ysolvn1(i))^2);
        end
    end
    for i = 1:length(xn2)
        if xn2(i) < xsolvn2(i);
            distn2(i) = -sqrt((xn2(i)-xsolvn2(i))^2+(yn2(i)-ysolvn2(i))^2);
        else
            distn2(i) = sqrt((xn2(i)-xsolvn2(i))^2+(yn2(i)-ysolvn2(i))^2);
        end
    end
    for i = 1:length(xn3)
        if xn3(i) < xsolvn3(i);
            distn3(i) = -sqrt((xn3(i)-xsolvn3(i))^2+(yn3(i)-ysolvn3(i))^2);
        else
            distn3(i) = sqrt((xn3(i)-xsolvn3(i))^2+(yn3(i)-ysolvn3(i))^2);
        end
    end
    for i = 1:length(xn4)
        if xn4(i) < xsolvn4(i);
            distn4(i) = -sqrt((xn4(i)-xsolvn4(i))^2+(yn4(i)-ysolvn4(i))^2);
        else
            distn4(i) = sqrt((xn4(i)-xsolvn4(i))^2+(yn4(i)-ysolvn4(i))^2);
        end
    end
end
\[
distn4(i) = \sqrt{(xn4(i) - xsolvn4(i))^2 + (yn4(i) - ysolvn4(i))^2};
\]
end
end
for i = 1:length(xn5)
if xn5(i) < xsolvn5(i);
    distn5(i) = -\sqrt{(xn5(i) - xsolvn5(i))^2 + (yn5(i) - ysolvn5(i))^2};
else
    distn5(i) = \sqrt{(xn5(i) - xsolvn5(i))^2 + (yn5(i) - ysolvn5(i))^2};
end
end
end

% Fitting a curve to each set of datapoints on the selected line

pn1 = polyfit(distn1, Major1, nn);
xn1 = min(distn1):0.1:max(distn1);
polynomialn1 = polyval(pn1, xn1);

pn2 = polyfit(distn2, Major2, nn);
xn2 = min(distn2):0.1:max(distn2);
polynomialn2 = polyval(pn2, xn2);

pn3 = polyfit(distn3, Major3, nn);
xn3 = min(distn3):0.1:max(distn3);
polynomialn3 = polyval(pn3, xn3);

pn4 = polyfit(distn4, Major4, nn);
xn4 = min(distn4):0.1:max(distn4);
polynomialn4 = polyval(pn4, xn4);

pn5 = polyfit(distn5, Major5, 4);
xn5 = min(distn5):0.1:max(distn5);
polynomialn5 = polyval(pn5, xn5);

%MinorStrains

pminn1 = polyfit(distn1, Minor1, nn);
xminn1 = min(distn1):0.1:max(distn1);
polynomialminn1 = polyval(pminn1, xminn1);

pminn2 = polyfit(distn2, Minor2, nn);
xminn2 = min(distn2):0.1:max(distn2);
polynomialminn2 = polyval(pminn2, xminn2);

pminn3 = polyfit(distn3, Minor3, nn);
xminn3 = min(distn3):0.1:max(distn3);
polynomialminn3 = polyval(pminn3, xminn3);

pminn4 = polyfit(distn4, Minor4, nn);
xminn4 = min(distn4):0.1:max(distn4);
polynomialminn4 = polyval(pminn4, xminn4);

pminn5 = polyfit(distn5, Minor5, nn);
xminn5 = min(distn5):0.1:max(distn5);
polynomialminn5 = polyval(pminn5, xminn5);
% Defining maximum Major Strain and minimum Minor Strain

MaxMajorNode = mean([max(polynomialn1) max(polynomialn2) max(polynomialn3)
max(polynomialn4) max(polynomialn5)])
MaxMinorNode = mean([min(polynomialminn1) min(polynomialminn2)
min(polynomialminn3) min(polynomialminn4) min(polynomialminn5)])

% Plotting all the data

plot(distn1,Major1,'b*')
hold on
plot(distn2,Major2,'g*')
plot(distn3,Major3,'m*')
plot(distn4,Major4,'r*')
plot(distn5,Major5,'y*')
plot(xn1,polynomialn1,'b')
plot(xn2,polynomialn2,'g')
plot(xn3,polynomialn3,'m')
plot(xn4,polynomialn4,'r')
plot(xn5,polynomialn5,'y')

plot(distn1,Minor1,'b*')
hold on
plot(distn2,Minor2,'g*')
plot(distn3,Minor3,'m*')
plot(distn4,Minor4,'r*')
plot(distn5,Minor5,'y*')
plot(xminn1,polynomialminn1,'b')
plot(xminn2,polynomialminn2,'g')
plot(xminn3,polynomialminn3,'m')
plot(xminn4,polynomialminn4,'r')
plot(xminn5,polynomialminn5,'y')

xlabel('Distance to crack')
ylabel('Strain')
title('Major and Minor limit strain calculation')
grid on