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Dome Tester

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Dome Tester Final Report

SENIOR DESIGN

MECE 471

HONORS PROJECT

MECE 497

By

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*Adapted from ECE445 guidelines, Univ. of Illinois

Abstract

We are reconfiguring and modifying the previously built dome tester to be more user friendly and mechanically applicable. This has a long-term goal of being a usable teaching tool for manufacturing education within the college of engineering and polymer sciences. The dome tester pushes a metal dome into a clamped sheet of metal to test its forming limits and where necking occurs. We have implemented a better method of viewing the sheet sample as it is being deformed, and improved measuring methods for the distance a sample is deformed. By introducing these changes in conjunction with improved documentation of the testing procedure we hope to make this tester a more viable teaching tool for students to learn manufacturing methods and considerations.

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1. Introduction

The Tabletop Dome Tester is a continuation project from previous years senior design teams. Although the end goals and overall purpose remain the same, some of the operational variables have been subject to change.

1.1 Background

"Dome Testing" is a term used to describe the sheet material deformation study of the elasticity and plasticity of a material. It consists of pressing an arbitrary shape, typically a dome, into a sheet metal specimen and continuing to press until the specimen reaches a point either just before or after failure. Commonly, a circle gridding pattern is etched onto the specimen's surface in order to mathematically calculate and plot the tensile and compressive forces taking place on the material. These circles, upon completion of the test, will result in ovals or eclipses with varying lengths and widths. Using a Mylar Strip Scale, this variation can be measured and then plotted onto a Forming Limit Diagram (FLD) to present the major strain and minor strain at different locations on the test specimen. Of course, this test can be completed using a variety of materials and material thicknesses. This is what we are expanding upon, making the lab process more efficient and student friendly so that anyone can operate the hydraulic press in order to obtain their own FLD.

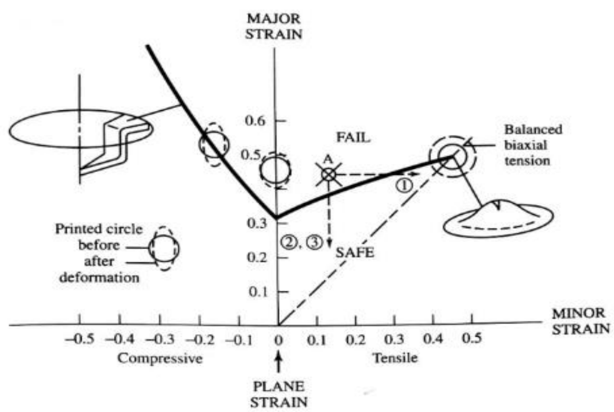

Figure 1 Forming Limit Diagram (Schey p. 409)

1.2 Our Goals

We began this project with the general goal of improving the currently operating dome tester. This came in a couple of stages as we learned more about how the press operates and its current limitations. Our goals changed throughout the process of this project. Within this report we will describe the efforts we took to learn about the press and other methods to complete our goals. We discovered multiple ways we can improve the press and through review of those methods we changed our plan of action multiple times.

Upon beginning the second phase of the senior design course, our goals and motives shifted slightly to a narrower plan. We were to implement a viewing method for watching the deformation of the sample being pressed, implement a displacement gauge to measure the travel of the hydraulic press head and sample dome (to calculate pressing distance to failure or necking) and finally to collect enough major strain / minor strain data from different materials and thicknesses to create FLD diagrams. This shift in motive has allowed us to pursue a project goal much more obtainable than thought before. Our deformation tester will then be accessible by all U.A. students and staff for educational and testing purposes.

2. Outline of Subject Matter

2.1 Introduction

The below block diagram / flow chart in **Figure 2** displays our main objectives in this phase of senior design. These blocks are of the major items we needed to complete, sub items such as ordering are not included. What is explained in the **Introduction** has been translated into this flow diagram.

What has been altered from phase 1 of senior design includes not inverting the hydraulic press but instead implementing a visual aid borescope *(see section 2.2.3 and 2.2.4)* to view the deformation from below and finalizing our press head travel / material deformation displacement measuring method *(see section 2.2.2)*. Included in both of these changes is the frame static mounting locations and methods. These iterations to our block diagram saved us two to three weeks overall considering the machine time that would be cut from having to fabricate an inverted press.

Also included in our diagram is the completion of two different FLD diagrams. Each diagram will be of a different material as well as four material widths with a constant length. The materials include two different thicknesses of carbon steel. The material widths include 1", 2", 3" and 4". These data collection points will provide us with a wide spread of major strain and minor strain data.

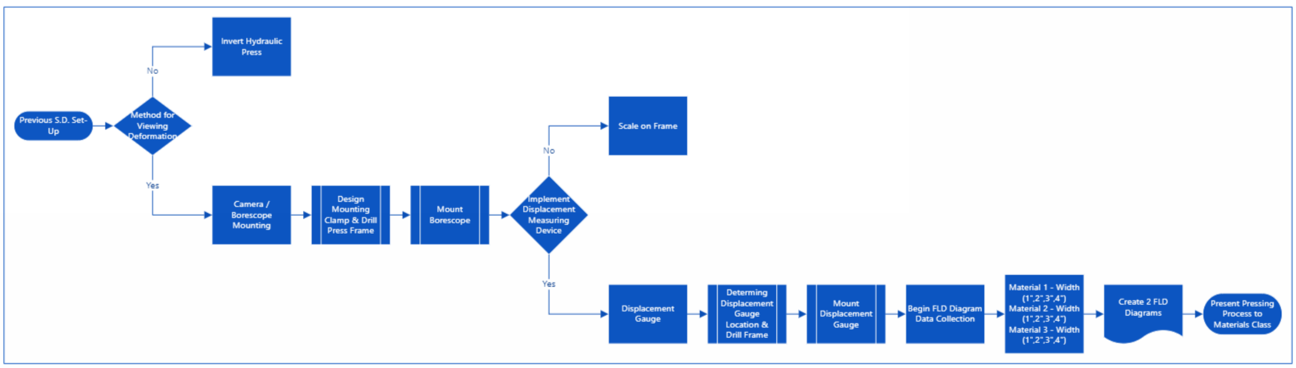

Figure 2

2.2 Design

2.2.1 Design procedure

The most prominent blocks in our decision diagram are the borescope implementation, displacement implementation and FLD diagram testing / creation.

The borescope mounting flourished from an alternative method to inverting the hydraulic press. This would be done in order to view the deformation of the sheet sample so that necking or fracture could be noticed. In changing this route, we saved a total of two to three weeks project finish lead time since a lot of machining could be ignored. This viewing method was also cost effective since no new material would need to be bought for fabrication of a new press base.

The press head travel / sheet material deformation measurement method was chosen to be a linear displacement gauge. This was done in order to obtain the greatest accuracy of measurement since any small deformation could be between necking and failure. We needed a cost-effective and accurate method to measure our dome height. The time of ordering to mounting was less then two weeks and we were then able to collect data for our FLD creations.

2.2.2 Design Details - Linear Displacement Gauge

Initially our displacement measuring method was a small ruler that was affixed to the stand of the press. This was a usable tool for measurement, though its resolution left some to be desired. We again employed a brainstorming session followed by a decision matrix to decide on what may be the best measurement method.

	Decision Matrix for Purchasing Displacement Measuring Tool												
Desired Criteria			Cost		Efficiency (How quickly are we able to identify the measurement?)		Practicality		Accuracy		Lifespan		
Criteria Weight			7		8		7		9		5		
			Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	
Displacement Measuring Methods	Description of Use												Total (Highest Possible Score of 268)
Tape Measure	Attach base to ground and the extentable end to the moving arm of the press.		7	49	6	48	4	28	9	81	4	20	226
Metal Ruler	Mark a zero position on the frame with an erasible marker, then measure the moving arm of the frames distance with respect to the ruler location.		7	49	6	48	5	35	8	72	3	15	219
Impliment Ruler Lines onto Frame	Mark lines onto the frame to identify a starting point of the press movement.		7	49	7	56	6	42	9	81	5	25	253
The Rollbot	Digital output "rolling" tape measure. Would attatch the side of moving portion of frame, this would measure the displacement from origin.		7	49	8	64	6	42	8	72	4	20	247

Table 1 Displacement Measuring Tool Decision Matrix

The above image in ***Table 1*** shows the decision matrix that we created in order to determine the best tool for measuring the displacement of the pressing mechanism. The displacement that we wish to measure is the travel from the pressing mechanism's starting point to the point where the pressing mechanism has pushed the metal dome into the metal sample to the point where necking is visible. At that point we would take the total measurement from start to end as our press' displacement.

Out of the four possible choices that we brainstormed and put into our decision matrix, the method that came out on top was "The Rollbot" with a matrix score 247. The Rollbot is essentially a digital output "rolling" tape measure that we could attach to the stationary frame of the press and then it would roll against the moving metal dome section of the press. Upon the sample being pressed and total travel of the metal dome achieved, the Rollbot would digitally readout how long from its origin the pressing mechanism had travelled.

Although now after some later consideration, a new contender has been thought over which involves a shorter measurable travel length and tighter tolerance. In our case, the tolerance needed for measuring the displacement as the sample begins to neck has to be under a tolerance of $1/32^{nd}$ or $1/64^{th}$ of an inch. An improved method of measuring this distance is a linear micrometer which would include a measurable travel length of 2 inches and a $\pm 1/64$-inch tolerance. The application of this tool would be the same as the Rollbot in attaching it to the stationary frame and measuring the moving pressing mechanism portion from its origin to its finish upon the sample necking. We included this alternative method in an updated decision matrix in ***Table 2*** to see if it compares to our previous choices. The linear displacement gauge ended up with a matrix score of 263 which far exceeds any of the other choices.

Decision Matrix for Purchasing Displacement Measuring Tool													
Desired Criteria			Cost		Efficiency (How quickly are we able to identify the measurement?)		Practicality		Accuracy		Lifespan		
Criteria Weight			7		8		7		9		5		
			Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	
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Impliment Ruler Lines onto Frame	Mark lines onto the frame to identify a starting point of the press movement.		7	49	7	56	6	42	9	81	5	25	253
The Rollbot	Digital output "rolling" tape measure. Would attatch the side of moving portion of frame, this would measure the displacement from origin.		7	49	8	64	6	42	8	72	4	20	247
Digital Displacement Gague with magnetic mount	Magnetic mount is affixed to the frame of the press and the dial is zeroed for when the dome touches the material. Allows for 1 inch of total displacement of the beam.		7	49	8	64	7	49	9	81	4	20	263

Table 2 Updated Displacement Measuring Tool Decision Matrix

This alternative method has now been implemented. It consists of a digital displacement gauge that measures down to the thousandth of an inch that was originally intended for use on a lathe or milling machine. ***Figure 2*** shows the gauge as it is installed onto the press. This allows for easy measurement of where on the press's throw the dome is, including how much the dome is displaced at the point of failure of the sample being tested. The display of the gauge is magnetic, and thus was placed close to the moving arm to be central and legible. The body of the gauge is attached to the press walls using M3 machine screws and standoffs. This allows the guiding foot of the press's moving arm to pass underneath the rail of the gauge.

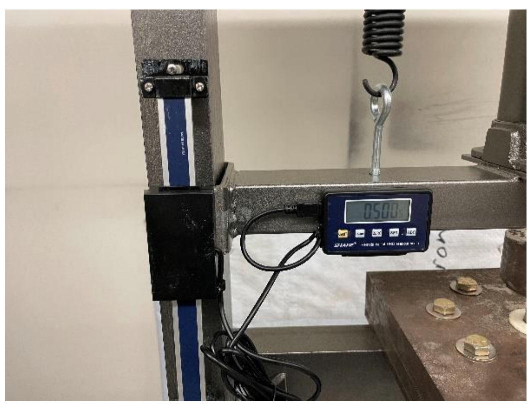


Figure 3 Digital Displacement Gauge

2.2.3 Design Details - Borescope Viewing

When we began this project, one area of concern was how to properly view the test sample being pressed. Two direct solutions to this issue that we brainstormed would have been to invert the pressing mechanism or implement a live video feed / camera to view the underside of the pressing die. The solution that we decided to pursue was to implement a live video feed / camera system so that we could view the material deformation without having to physically invert the pressing mechanism.

The first live feed video camera that came to our mind was a borescope. Professionals use these tools to inspect fine details in smaller areas of where they are working. For our application, we will use this tool to view the contact position of our press head, necking of our material and fracture of our material. This would also allow us to view the deformation of the material at an up-close range. Since we have our circle grid pattern chemically etched onto our samples surface, viewing the plastic deformation of our material using this tool is quite straight forward.

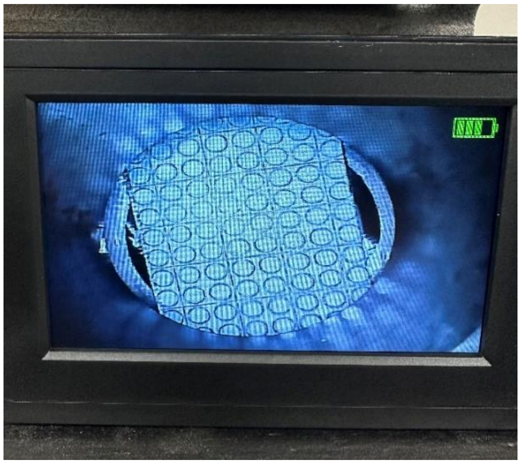


Figure 4 Borescope Visual

Figure 5 Borescope Location

As seen above in ***Figure 3*** and ***Figure 4***, this is how the borescope that we implemented views the test sample and seats on the press mount. The borescope itself is a SKYBASIC Industrial Endoscope Borescope that we purchased off of Amazon.com.

Upon using this tool, we have found that it works well once you are familiarized with the pressure felt in the pump handle in correspondence to how the sample is viewed in deformation. Necking can usually be seen as a small indentation around the area that the press head is contacting. Once this necking is visible, we will remove the sample from the press and measure the circle deformation accordingly with the Mylar strain scale.

2.2.4 Design Details - Borescope Mounting

The Borescope is mounted using a custom designed bracket. This bracket was 3d printed in The University of Akron College of Engineering 3d printing lab. This bracket is designed to both fix the camera's position on the press as well as allow for easy adjustment to its positioning. The planar positioning of the scope is adjusted using a M6 socket headed screw with a wingnut that is fit within a slot on the bracket. This allows radial and angular adjustments within the plane. Additionally, the vertical position of the borescope can be set within an attached clamp controlled by a M3 machine screw. The vertical position augments the borescope's built in zoom feature to allow for precise control of what is shown on the scope screen. ***Figure 5*** below shows the 3d model of the bracket and technical drawings can be found in ***Appendix A***.

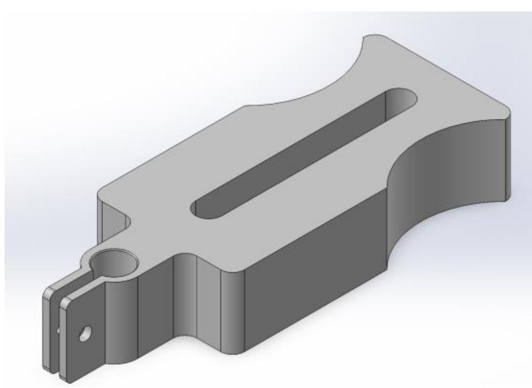


Figure 6 Borescope Mount

2.2.5 Codes and Standards

Some of the codes and standards considered while completing this project include protecting public health & safety, cost & implementation among communities, and reliability & efficiency in any design. Ensuring that products will provide safety while reducing their possible overall danger is what leads to making public health & safety one of the most important standards and influences when engineering products that anyone can use. We want to make sure that humans can conduct this experiment to its fullest extent without presenting any form of danger to their well-being. We want any person using any product or mechanical design to do so without the fear of harm towards themselves or others. Cost & implementation can be explained as, can an idea be engineered for low cost and will it ergonomically fit inside of a community or for community use which in this case would be the University of Akron. We want our improvements and implementations to be easily usable to the public whether it be the press itself, borescope or displacement gauge. These improvements should also be ergonomically suitable for their environment such as suburb or rural areas. Finally, reliability and efficiency are the goals for all engineering designs. Codes and standards that enforce this make sure that anything made available to the public will work correctly, efficiently, and provide a long operational life so that anyone under the right conditions can use the design without failure.

One major outcome that we have achieved by working on this project is to be able to provide this hydraulic press Erichsen Cup Test to any person and student at The University of Akron, so they are able to conduct their own tests and experiments with it. By opening this equipment up to the university public, it will allow anyone who has little to no lab environment work experience to be able to come in and learn how to properly work in that new environment on university testing equipment. This is not limited to those who have little to no experience, this would also be open to those who already know how to use the lab and its equipment.

2.3 Verification

After we implemented our improved deformation viewing and displacement measuring techniques via mounting to the test frame, we were then ready to begin testing. Our main test was to verify if the dome tester was user friendly, ergonomic and able to be used with greater ease than before. To complete this test, we operated the deformation press as intended, collecting pressed samples of different materials and thicknesses in order to complete two different forming limit diagrams which could be displayed.

Some of the roadblocks that we encountered while developing methods to operate the pressing process with greater ease included the following. First, we began with a design decision as to whether or not we should invert the pressing mechanism entirely, which would involve great cost and extensive design, or implement a direct feed viewing method which would only include mounting and calibrating to the deformation location. We chose the lower cost / faster lead time option, which was to purchase a direct feed borescope, design and implement a clamp to center the camera to our test sample, and to mount the screen for easy visibility.

Our next roadblock was identifying a fixed method on how to etch / paint measurable patterns onto our test samples in order to measure the deformation tensile strains. After communicating with several U.A. staff members and developing a plan with Dr. Gopal Nadkarni, we located a contact who would be able to explain to us how to use the equipment that we had in the laboratory (which was previously not known how to operate) to chemically etch a circle grid pattern into our sheet metal. This pattern would display elongated circles based on dome location which could be measured and identified based on shape whether or not a location was under tensile or compressive stresses. We learned how to operate the etching machine and its components in which we then created a fixed standard operating procedure for future student and faculty use. This procedure is shown in ***Appendix C***.

Finally, our last major roadblock was determining how to properly measure the displacement of our press head and sheet metal deformation with high accuracy. After creating a researching and creating a design matrix of all of the different possible choices (***Table 2***) we narrowed down our best choice to be a linear displacement gauge used normally on lathes. After discussing and implementing a permanent mounting location, this gauge provided us with accurate data that measured down the half-a-thousandth.

2.3.1 Verification – Forming Limit Results

As stated in section ***2.3***, we conducted forming limit deformation testing so that we could verify the ergonomics of our dome tester implementations.

A forming limit diagram is a method for collecting data on different kinds of deformation per area measured on a sheet metal same and also a method for predicting necking / different areas of failure in a material (Refer to ***Figure 1***). This is done by taking measurements of the circle pattern (explained in section ***2.3***) with a Mylar strip gauge which will then tell you the elongation of the test material in that area. Elongation in this case will mean the major strain (ε_1) and minor strain (ε_2) values, the circles will stretch to become ellipses that can either stretch in the x or y direction.

We made 2 different forming limit diagrams from 2 different materials. Each material was cut into four separate widths with a constant length. Six circles were measured for each of the four samples per material.

Our first material was a standard carbon steel with a thickness of 0.026”. Lubrication (cling wrap) was added to each sample to decrease the amount of friction between the head of the press and our sheet sample. This would minimize the chance of tearing.

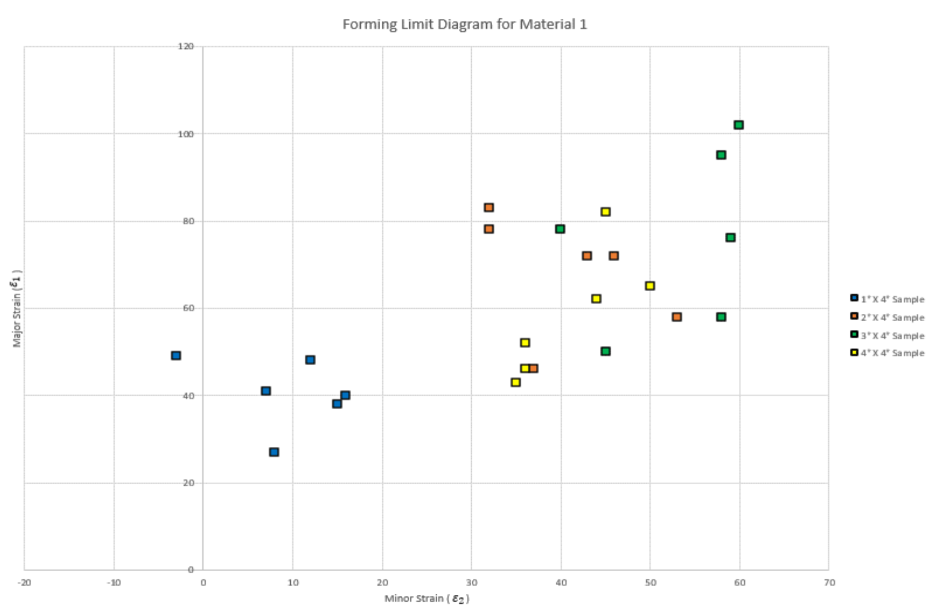


Figure 7 Material 1 FLD

Shown in ***Figure 7*** is the forming limit diagram obtained from the four samples deformed from material 1. The larger the sample area becomes, the greater the major and minor strains that are allowed before necking or failure of the material takes place. This material exhibited great elongation along with a decent ultimate strength when compared to a zero carbon content sheet of metal.

The second material we chose to deform was a steel used mainly for car door manufacturing. It had a thickness of 0.023” and a heat number of #5092453. This was specially obtained through Dr. Gopal Nadkarni.

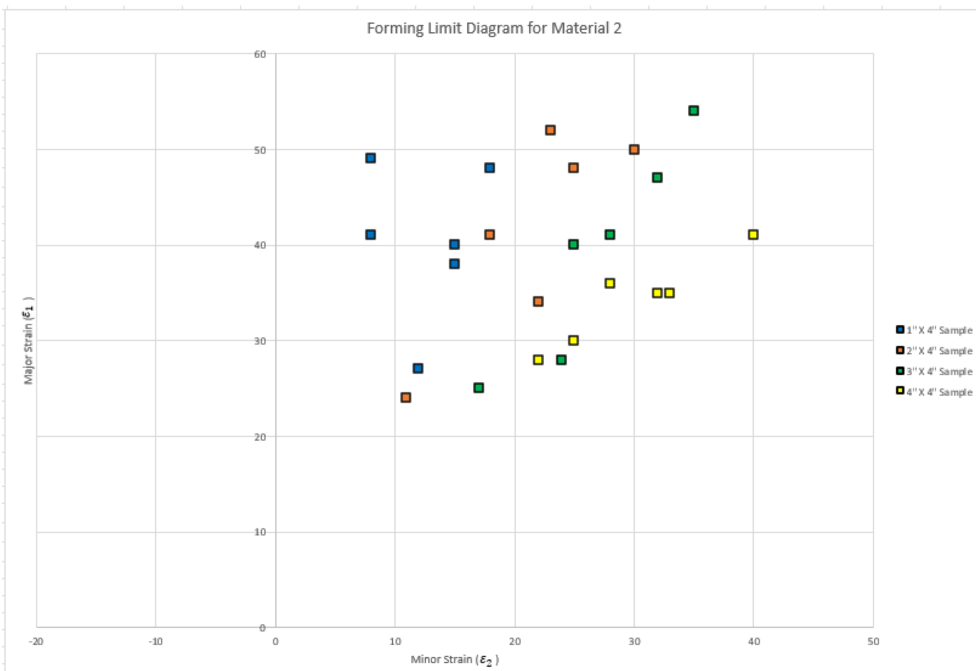


Figure 8 Material 2 FLD

As shown in ***Figure 8*** this car door steel was much less able to be elongated by the dome press. Lubricant was still added in the form on cling wrap to minimize the amount of friction applied to the sample. With the controlled variables the same, and the material different, this steel exhibited a much more grouped set of results. No matter the area increase, the major and minor strains stayed relatively close with minimal differences. Each sample was brought to a state of necking, this took place very quickly with respect to the previous material 1 steel. Based on our findings, we decided not to plot the estimation curves due to the data grouping together in this way. We found very similar points of necking and failure amongst the four samples.

Included below is photos of each sample to provide a visualization of the amount of deformation each as able to experience before a point of necking or failure took place. Due to the low amount of carbon content in material 1, it was able to elongate much further before reaching failure. Since material 2 is used for car doors, it is assumed the carbon content is higher since it reached necking criteria much earlier in the pressing.

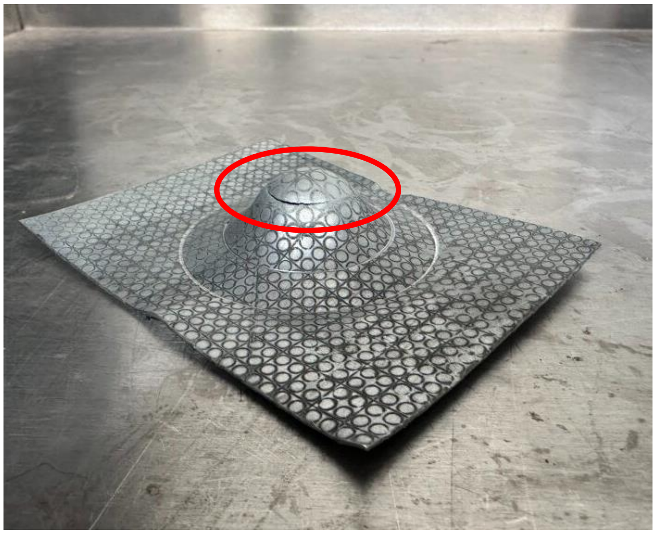


Figure 9 Material 1

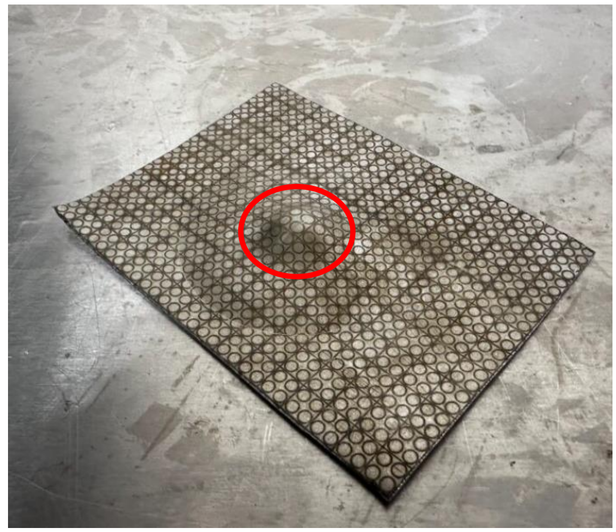


Figure 10 Material 2

Figure(s) 9 & 10 display the sheet samples after being pressed and reaching a point of necking or failure. It is important for us to record our measurements from elongated circles in the area of necking, NOT failure. Based on material 1's elongation, its ultimate tensile strength was tested to be much higher than material 2. This caused material 2 to reach necking much earlier than material 1. These photo's also present the ellipses circles measured to obtain the forming limit diagrams per material tested which is hat students and staff will accomplish by using this laboratory.

Next, we compiled the average points for each sheet samples (average of the 6 major and minor strain points measured per sample) and plotted them in order to determine a trendline of the data. This would allow us to better compare our own measured data against one-another and to compare our measured data to average forming limit values recorded in the industry.

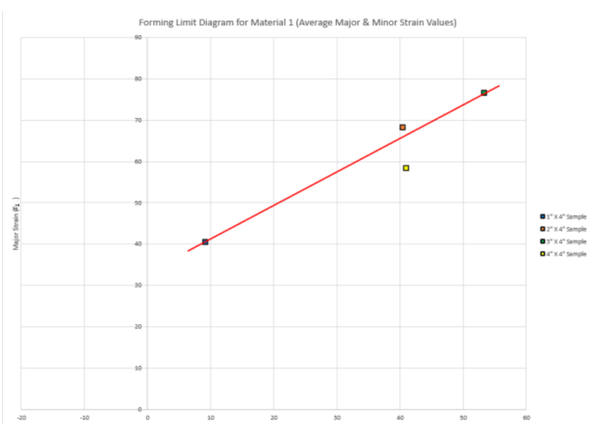


Figure 11 Material 1 Average FLD

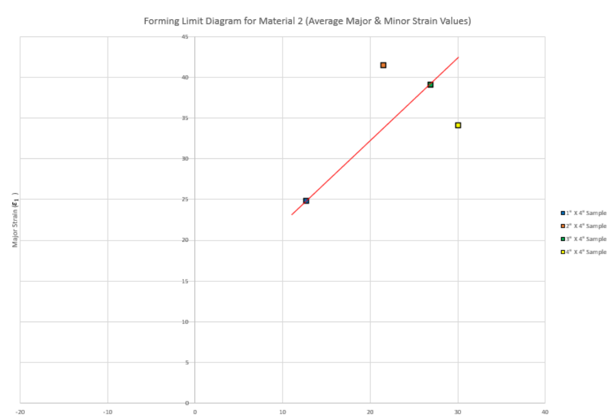


Figure 12 Material 2 Average FLD

In the following figures, we have displayed typical forming limit diagrams from tests performed in the industry. The first diagram will be for a typical low carbon steel and the second will be for a mild steel used for car door manufacturing.

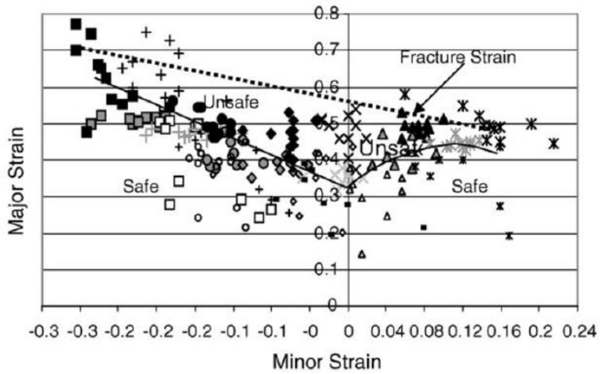


Figure 13 Typical Low Carbon Steel FLD

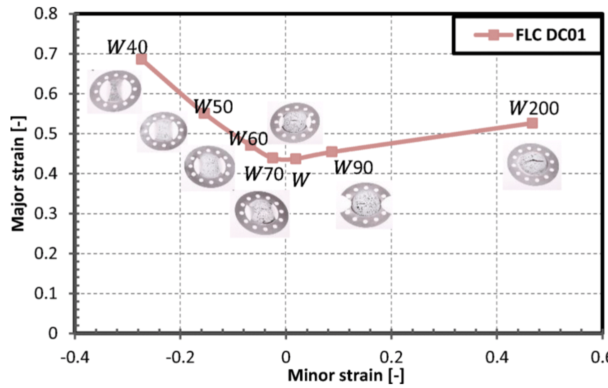


Figure 14 Typical Mild Steel FLD

Compared to our measured low carbon steel samples, ***Figure 13*** provides a similar FLD with respect to its average trendline. The main point of focus between the similarities between our FLD and the typical FLD of low carbon steel is that as sample surface area increases, major strain and minor strain that the sample experiences will increase in the positive tensile. Onto ***Figure 14***, this compared to our created FLD is completely different and we believe that we know the reasoning behind this. This difference is most likely due to the environment that the sheet metal has been exposed to. The sheet metal has been in the laboratory for over a semester where there is a furnace, thus it is very warm in the room. Long exposure to this before we had the chance to cut and test the material might have led to altered mechanical properties. Given the differences in the mild steel FLD and our own, there are similarities in the plateau of major and minor strain values after a certain area of sample is reached. Elongation and yielding criteria bunch together in the greater area samples where there is minimal change between the sheet deformation and point of failure (press dome displacement).

2.4 Costs

The average labor cost estimate for each group member is presented by the following formula:

$$ideal\ salary\ (hourly\ rate) \times actual\ hours\ spend \times 2.5 = Labor\ Cost\ Estimate \quad (4.0)$$

For Nikolas Kulin

$$\$21.00\ per\ hour \times 4\ hours\ per\ week \times 2.5 = \$210.00\ per\ week$$

For Clark Bates

$$\$21.00\ per\ hour\ \times\ 4\ hours\ per\ week\ \times 2.5 = \$210.00\ per\ week$$

We have each spent an average of 3 to 5 hours a week working on phase 2 of our senior design project. This has taken place in the lab where the dome tester is located or elsewhere on technical portions of the project.

3. Conclusions and Further Resources

By the end of this project the operation of the press was clearly more efficient and easier. Having the borescope and the displacement gauge allows the operators to quickly and easily verify both if their sample has failed or begun to neck at any points, as well as how far the press has displaced the material. This displacement measurement allows operators to predict approximately when the material will fail. Using this knowledge operators can predict where their sample may fail and expedite the travel of the tester before approaching this point. Combining these factors, the tester has become more efficient as both a tool for gathering data and for teaching students.

Regarding using the tester as a learning tool, the procedures that now document the process also improve the tester's effectiveness for student use. Reading through the procedures alone teaches students how this sort of test is performed, and additionally this can prepare them for experiential learning by operating the press. These features alone make the generation of data very straightforward, allowing the operators to focus on the interpretation of the data as opposed to the collection of data. Based on the experience of our senior design team, the actual plotting of the forming limit diagrams was a very quick and simple process once the sample data was generated. By improving the sample testing process this targets the most difficult part of the lab, making it much more approachable to students.

The etching process was initially something of a "black box" where students would not have any indication of how the etching process happened and what it physically did to the sample material. Our procedure for how it is done came from a personal interview with Dr. Danny Schaeffler conducted on October 4^{th,} 2023, and it greatly empowers tester operators to understand why the gridding works for this application. Additionally, this gridding procedure helps to improve the safety of any student learning to produce their own testing materials.

Based on our presentation of this material to a manufacturing lab class, our process can be completed in a standard class time. Discussing the material with the class took most of the class period, and data generation and measuring was a relatively fast and simple part of the presentation. Interpreting the results of our test and determining how a given material's properties affect the results took the forefront of the class session. This perfectly illustrates the goals of our modifications of the press. Operation of the tester has been improved enough that it is a much more useful learning tool.

References

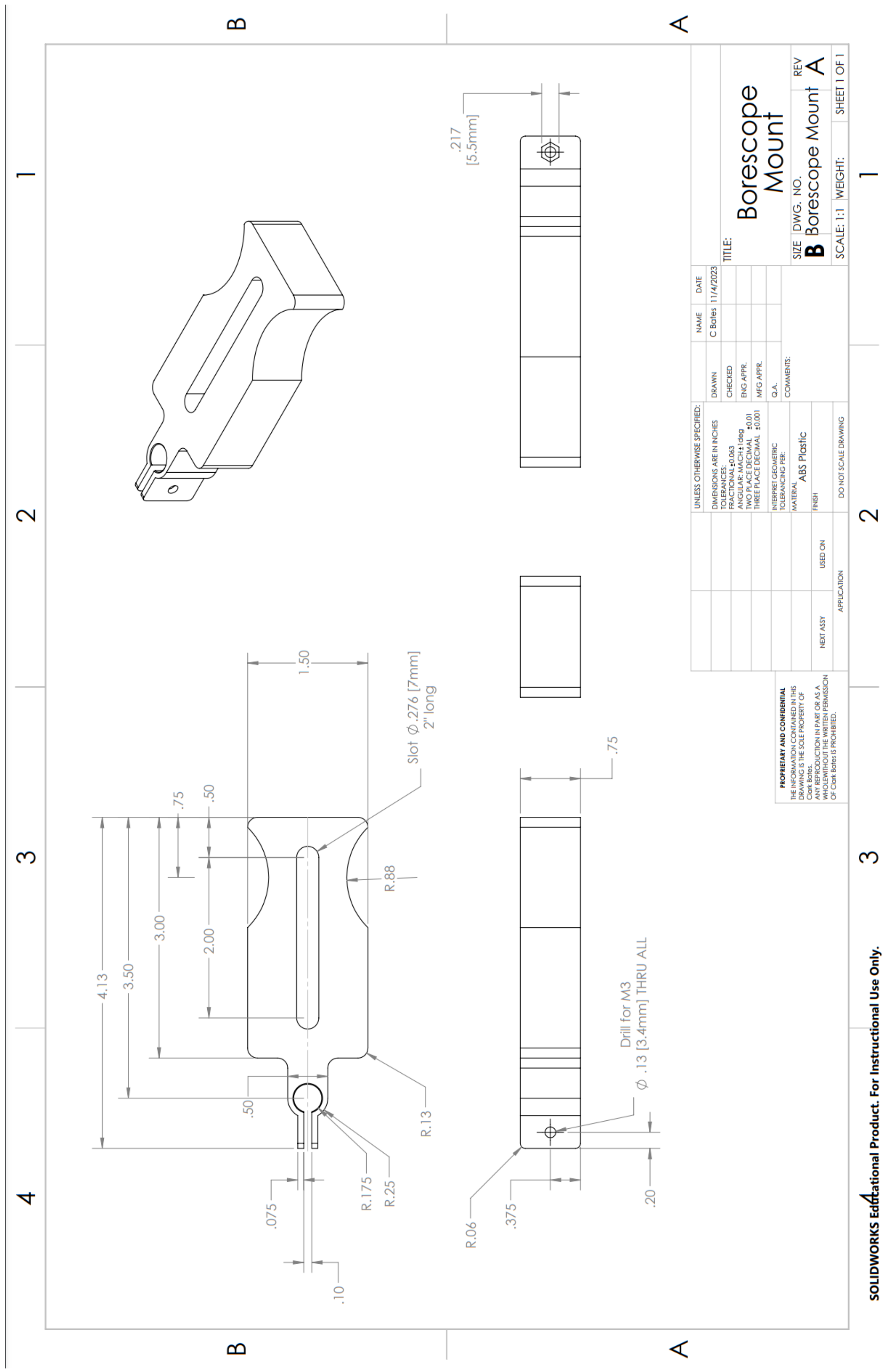
[1] ***Figure 13***: Krishnaswamy, Hariharan & Nguyen, Ngoc-Trung & Barlat, Frederic & Lee, Myoung-Gyu & Kim, Ji-Hoon. (2014). A pragmatic approach to accommodate in-plane anisotropy in forming limit diagrams. Mechanics Research Communications. 10.1016/j.mechrescom.2014.07.007.

[2] ***Figure 14***: Farahnak, Pedram & Urbánek, Miroslav & Konopik, Pavel & Džugan, Jan. (2020). Influence of thickness reduction on forming limits of mild steel DC01. International Journal of Material Forming. 13. 10.1007/s12289-019-01513-3.

[3] Schey, J. A. (2000). *Introduction to manufacturing processes*. McGraw-Hill.

[4] Hashemi, Ramin & Karajibani, Ehsan. (2016). Forming limit diagram of Al-Cu two-layer metallic sheets considering the Marciniak and Kuczynski theory. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 232. 10.1177/0954405416654419

Appendix A Borescope Mount Drawing



Appendix B Circle Grid Chemical Etching Procedure

Test Material Circle Grid Chemical Etching Procedure

Standard Operating Procedure

Department: Mechanical Engineering
Author(s): Nikolas Kulin and Clark Bates
Date: 11/06/23

Purpose

This S.O.P. is being written in order to provide instructions on how to chemically etch the circle gridding pattern onto any sheet of material. It will also ensure that proper results are obtained so that the subsequent processes can yield adequate data.

Scope

Students/Individuals who have access to Dr. Gopal Nadkarni's laboratory and who will be using the hydraulic sheet deformation press will need to review this information before conducting any sheet metal pressing.

Equipment

- Sheet metal which the circle grid pattern will be etched onto
- Scrap sheet metal to conduct electricity
- Soft Cleaning Cloth
- Felt Sheet
- Circle Grid Template
- Nitrile Gloves
- Safety Glasses
- Electrolyte
- Lectroetch AC/DC etching apparatus
- Lectroetch Rollermarker and Ground Clamp Cord

Definitions

- **Electrolyte**: Liquid electrically conductive solution used for etching ferrous alloys, electroplated zinc and cadmium.
- **Circle Grid Marking**: Template to evaluate the effects of deformation. Depending on the shape of a circle in a provided area, major and minor strain can be evaluated.

Procedure

- **Step 1:** Locate an area with a non-metal work area and a sink / rinsing drain.

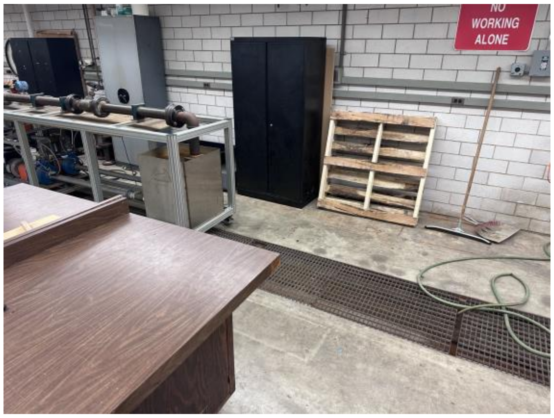


Figure 1

- **Step 2:** Gather all of the equipment and material needed.
- **Step 3:** Lay a scrap sheet of metal onto the non-metal work area.
- **Step 4:** Place the sheet metal that will be etched into on top of the scrap sheet of metal.
- **Step 5:** Use a soft cleaning cloth (soft so that no scratching or scraping of the materials surface occurs) to wipe down the materials surface of any oils or dirt.
- **Step 6:** Put-on safety glasses and nitrile gloves.
- **Step 7:** Pour a thin sheet of Electrolyte onto the surface of the sheet metal that will be etched.
    - **Step 7.1:** Spread this sheet evenly onto the surface in which the circle grid template will cover (can be spread with hands if nitrile gloves are worn).
- **Step 8:** Place circle grid template onto Electrolyte sheet
    - **Step 8.1:** Entire area of the template should be damp with Electrolyte so that it can hold to the sheet metal.

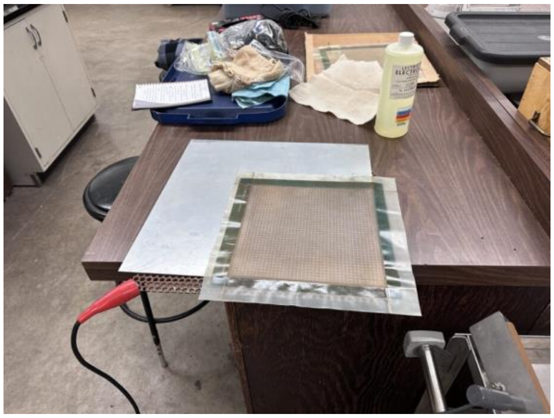


Figure 2

- **Step 9:** Place the felt sheet on top of the circle grid template.
- **Step 10:** Pour Electrolyte onto the felt sheet until the sheet is damp.
  - **Step 10.1:** If nitrile gloves are worn, this Electrolyte can also be spread so that the amount poured onto the felt sheet can be maximized.

Figure 3

- **Step 11:** With the Lectroetch apparatus OFF flip the LEFT switch UP to AC, flip the MIDDLE switch DOWN to INT. OFF and turn the BOTTOM RIGHT knob to 60.

Figure 4

- **Step 12:** Attach the ground clamp (encompassed in red rubber) to the scrap sheet of metal.

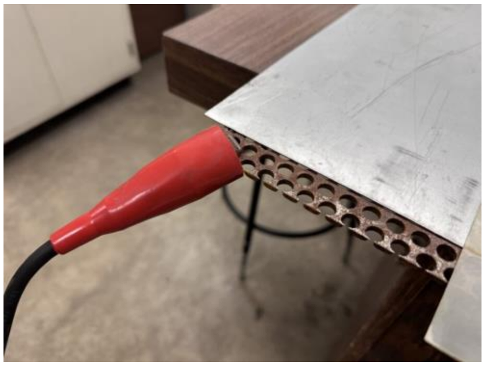


Figure 5

- **Step 13:** Ensure that all connections are made.
    - Ground wire / Lectroetch Rollmarker connection is attached to the Lectroetch apparatus and the Lectroetch apparatus is plugged into a power source.
- **Step 14:** To begin etching, PICK-UP the Lectroetch Rollmarker and then flip the power switch on the Lectroetch apparatus to ON.
    - **Step 14.1:** The Lectroetch Rollermarker is now LIVE and has voltage running through it.
    - **Step 14.2:** Verify that the VOLTS dial is showing 15-16 volts.
    - **Step 14.3:** WITHOUT MAKING CONTACT WITH ANY METAL (or else you will receive a shock) begin rolling the Lectroetch Rollermarker over the saturated felt sheet. Small sparks and cracks should be heard as verification that the etching is taking place.
- **Step 15:** Roll the Lectroetch Rollermarker down and back over top of the felt sheet 6-8 times. This will ensure that the etch penetrates the sheet metal.
- **Step 16:** Once finished rolling, carefully pull up a corner of the circle grid template to check that the etch has been applied.

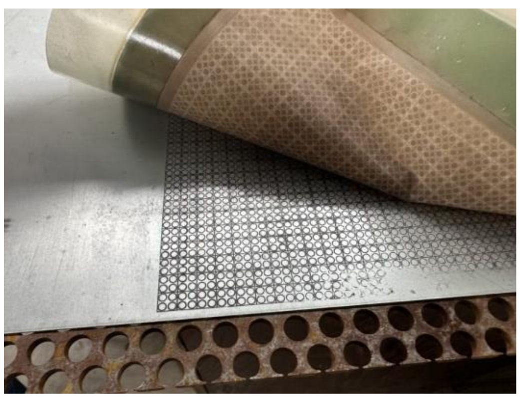


Figure 6

- **Step 17:** TURN OFF the Lectroetch apparatus before doing anything else.
- **Step 18:** Once the Lectroetch apparatus is off lay the Lectroetch Rollermarker onto a cloth, disconnect the ground clamp, dropping it onto the floor, and unplug the Lectroetch apparatus from the power source.
- **Step 19:** Clean off the Electrolyte from the circle grid template and felt sheet using a thorough amount of room temperature water. (Let the sheets air dry)

You have now completed the circle grid chemical etching procedure

Appendix C Test Material Forming Limit Lab Procedure

Test Material Forming Limit Lab Procedure

Standard Operating Procedure

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Date: 11/13/23

Purpose

This Standard Operating Procedure is written in order to provide detailed instruction on how to properly operate and conduct the sheet material deformation lab. It will also ensure that adequate results are able to be obtained upon completion of the lab.

Scope

Students/Individuals who have access to Dr. Gopal Nadkarni's laboratory and who will be using the hydraulic sheet deformation press will need to review/reference this information before/during conducting any sheet metal pressing.

Equipment

- Central Machinery 20 Ton Shop Press
- Central Machinery 20 Ton Hydraulic Bottle Jack
- Sheet Material Die (Male & Female)
- Dome Head Attachment for Press
- SHAHE Linear Displacement Scale
- SKYBASIC Industrial Endoscope Borescope
- OEMTOOLS 1/2in Drive Torque Wrench
- Crescent Wrench
- Eight ½"-13 Grade 8 Bolts
- Sheet Material of Choice – <u>Circle Grid Pattern Etched</u>
    - Refer to *Test Material Circle Grid Chemical Etching Procedure*
- Shears for Cutting Sheet Sizes
- Mylar Strip Scale
- Lubricant (Grease, Trash Bag or Cling Film)
- Safety Glasses
- Gloves

Definitions

- **FLD:** Forming Limit Diagram
- **Circle Grid Pattern:** Pattern to help measure material stretching or drawing per the pressing motion.

Procedure

- **Step 1:** Gather all materials listed in the **Equipment** section and equip safety glasses and gloves.
- **Step 2:** Before any sheet deformation testing can be set-up or performed, it is important to have your sheet material prepared for future deformation measurement.
  - To properly prepare your sheet metal of choice, reference the *Test Material Circle Grid Chemical Etching Procedure*.
- **Step 3:** Once your chosen sheet metal is chemically etched with the circle grid pattern, you are now ready to begin the sheet forming limit test.
- **Step 4:** Start by cutting samples from the sheet metal using shears. Cut samples of 1", 2", 3" and 4" widths with a controlled length which will cover the through holes of the male and female dies (e.g. 4" in length).
- **Step 5:** Next, verify the lengths and widths of the sample pieces to ensure proper data is collected during the test.
  - Remove any burrs from the edges of the samples using a file.
- **Step 6:** If not done so already, walk over to the press and remove the top male half of the sheet material die.
  - The easiest way to do this is to rotate the die 45 degrees so that the corners can act as handles. Lift the die from the corners and carefully lay it on another surface.
- **Step 7:** First take the 1" x controlled length" sample and lay it centered, vertically and circle grid pattern facing down on top of the bottom half of the die.
- **Step 8:** Cut a trash bag or piece of cling wrap to the size of the sample and place on top of the sample. This will act as lubricant (grease may also be applied to the top exposed face of the sample as well).
- **Step 9:** Carefully place the top half of the die back onto the sheet sample/bottom half of the die. Do this in the same orientation as you removed it before.
  - **BE CAREFUL NOT TO SHIFT THE SHEET SAMPLE / LUBRIACANT.** It is important to keep the sample centered to the die hole.
- **Step 10:** Once the top and bottom halves of the die are oriented and "sandwiching" the sheet sample and lubricant, the torquing process may now take place.
- **Step 11:** Obtain the eight ½"-13 grade 8 bolts that are provided and drop them into each of the eight bolt holes in the die. Hand tighten the corresponding nuts to the bolts ensuring one washer on the bolt-head- end and one washer on the nut-end.
- **Step 12:** Once the nuts and bolts are hand tightened, obtain the torque wrench and crescent wrench provided. Secure the crescent wrench to a nut and the torque wrench to the top of the corresponding bolt. Torque the bolt to 9ft*lbs~10ft*lbs.
  - Repeat this step for all of the other bolts making sure to go in a star-like pattern as if installing a tire onto a vehicle.

- **Step 13:** Ensure that all bolts are not loose by nudging them with your hand. If any seem to be loose, torque to the specification listed in **Step 12**.
  Step 14: WITH TWO PEOPLE, one on either side of the die platform, lift the platform
- **Step 15:** Turn on the borescope camera and ensure that the bottom face of the test sample can be seen on the screen.
- **Step 16:** Turn on the displacement gauge. There is no need to zero it quite yet.
- **Step 17:** Begin pumping the hydraulic bottle jack, moving the dome downward towards the sample.
- **Step 18:** ONCE THE DOME MAKES CONTACT WITH THE SAMPLE, you will notice movement on the borescope screen, then zero the displacement gauge.
- **Step 19:** Continue pumping until necking is noticed or failure occurs.
  - Necking will resemble concaving around the area that the dome is contacting.
- **Step 20:** Once necking is noticed or failure occurs, stop the test and record the distance displayed on the displacement gauge. This is the travel distance it took for the material to reach failure.
- **Step 21:** Remove the sample from the die.
- **Step 22:** Using the Mylar Strip Scale, measure the major and minor strain of the material. To do this reference the photo below. Measure circles only around the area of necking / failure.

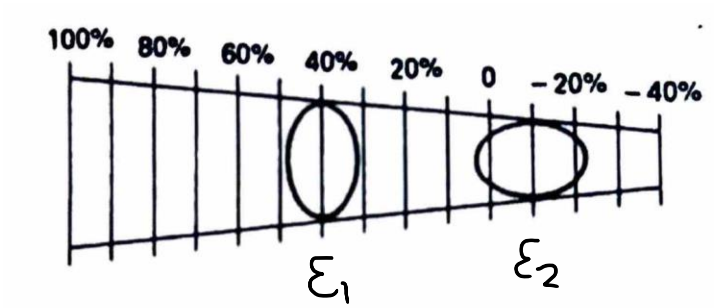

Figure 1

- **Step 23:** ε_1 is the major strain and ε_2 is the minor strain. Both represent the percentage of strain in the allotted direction. Major strain represents the y-axis (y-value) and minor strain represents the x-axis (x-value).
- **Step 24:** Measure both major and minor strain values for 6 circles around the area of necking / failure.

- **Step 25:** Once 6 x,y coordinates are obtained, plot them to create your own forming limit diagram (FLD) for your choses material and geometry tested. An example diagram is shown below –

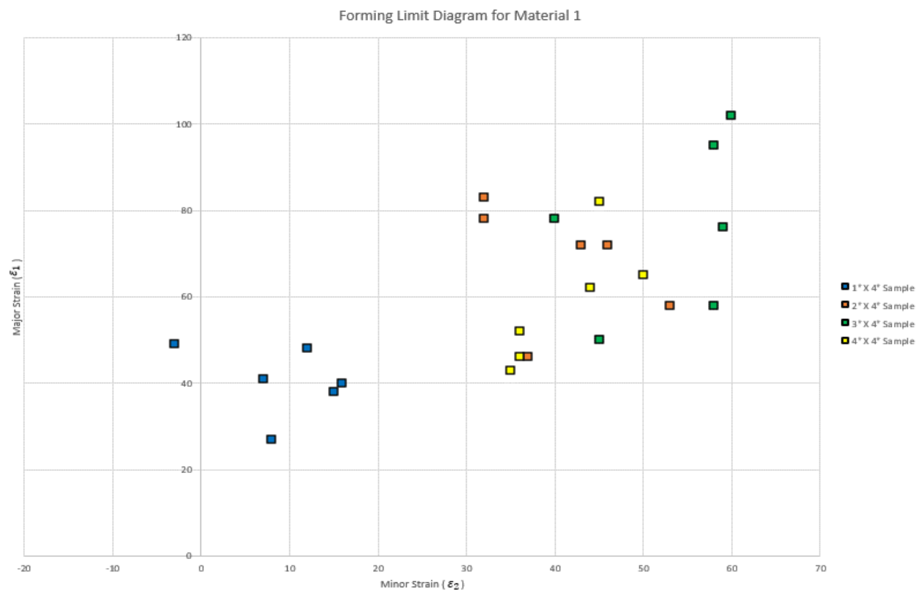

Figure 2

- **Step 26:** Three to four different geometries / widths of a material are normally pressed and plotted to show how difference in area affects the amount of force needed to cause necking or failure. Reference the four sample sizes taken above in ***Figure 2***.

You have now completed the sheet metal deformation test.