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Table Top Dome Tester

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Table Top Dome Tester Senior Design / Honors Project Report

The University of Akron College of Engineering

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Abstract

The Erichsen Cupping Test was used as a basis to design a dome tester. The intention of a dome tester is to test sheet metal material properties in all directions. This was done by clamping a piece of sheet metal and using a piston and hydraulic press to punch through the material. The force used to punch the material and the height of the deforming material can be gathered and the sheet metal properties can then be calculated. At the end of the project the team was able to successfully design and manufacture a hydraulic dome tester. However, due to unforeseen circumstances, the final assembly was unable to be tested. The machine should be capable of loading samples up to 20 tons with a stroke length of 2.0 inches. The dome tester currently resides in the manufacturing lab at the University of Akron where students will perform the stampability test themselves. They can apply real life engineering theory and study material properties of sheet metal during their coursework.

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Introduction

Background

Sheet metal is a thin piece of metal that is typically formed by rolling or hammering and is used to create a variety of different products. During the manufacturing process the sheet undergoes various operations such as punching, drawing, and forming. These processes are all either a stretch, a draw or a combination of the two. A stretch refers to a change in the thickness of the sheet metal and a draw refers to a deformation that does not result in a change in material thickness. In most circumstances a tensile test is used to determine material properties such as tensile strength, elastic modulus, elasticity, and plasticity. A tensile test is when a dog-bone shaped material sample is pulled until failure. The issue with this test is that it only tests the material properties in one direction (Budynas p. 42-43). Many materials have different material properties in different directions. This is normally not an issue in traditional machined parts, as they are not often loaded to the point where the material starts to deform permanently (also known as yielding). When using sheet metal, it is important to know the material properties of a piece in all directions in order to select the correct alloy for the desired operation. If a material that is too weak is chosen, the sheet metal can break or crack during the manufacturing process. Selecting a material that is too strong will likely result in a higher cost (Theja pg. 52).

Some tests already exist for evaluating material properties in different directions. One such test is the Erichsen Cupping Test, which was used as a launching-off point for the design team's research. This cupping test is the basis for what this project will try to create on a smaller scale, and at a lower cost. A general layout for the Erichsen Cupping Test is shown in Figure 1.

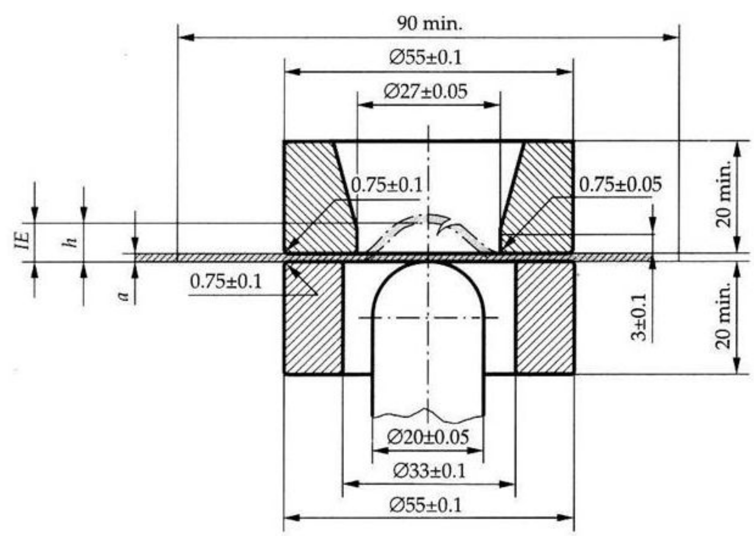

Figure 1: Erichsen Cupping Test Diagram (Theja)

The clamped piece of sheet metal is pushed on with a dome until fracture, and then the height of the cup can be measured. More information can also be gathered by printing a grid pattern or uniform circles in different locations on the test blank. During the test, the printed shapes will stretch out along with the material. Once the test is completed, new dimensions for the grid or circles can be measured to get strain in two different directions (Schey p. 408). Each location will have different amounts of strain due to the shape of the dome. These two different strain measurements are called the major and minor strains, and are used to create a *forming limit diagram* (FLD) which is shown in Figure 2. This application is very useful for sheet metal forming in industry and manufacturing, as the FLD can help identify problem areas with a fracturing part.

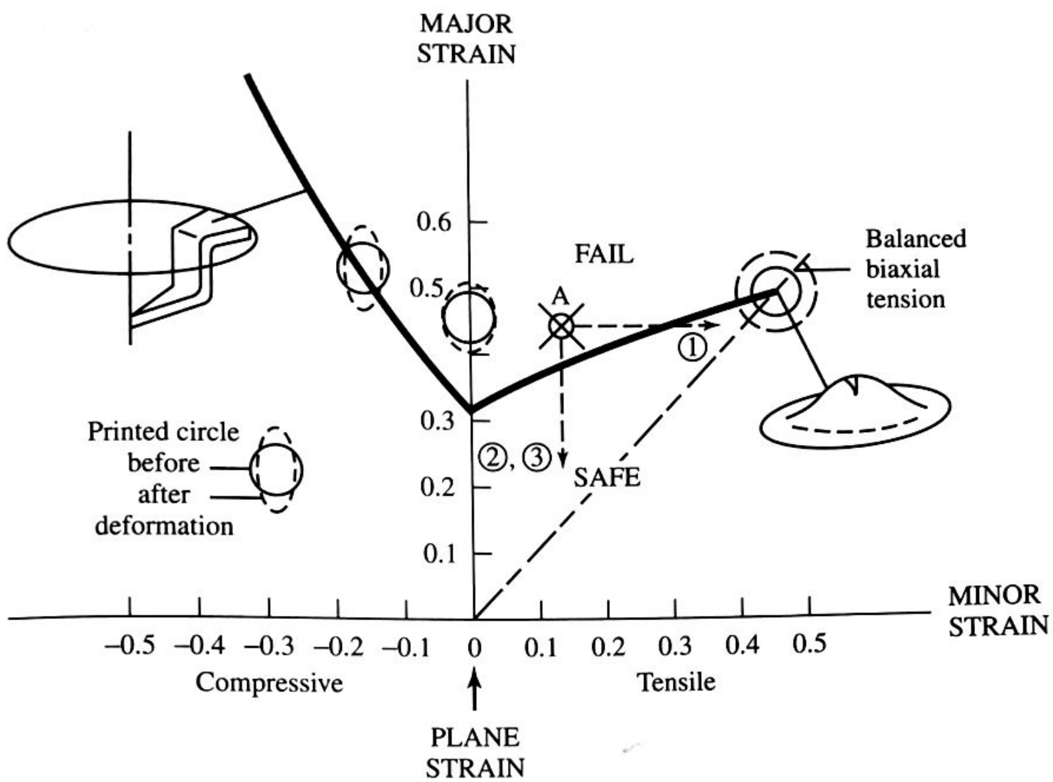

Figure 2: Forming Limit Diagram (Schey p. 409)

Currently, there are advanced imaging techniques and sensors that exist and automatically measure the change in the printed shapes during the test (Jinan Victory Testing). This method allows for FLDs to be created very quickly and efficiently. However, the same results can be achieved by doing hand measurements. FLDs take many tests and a lot of data to fill out; creating a forming limit diagram is not the end goal for this design project. Rather, the table top dome tester is to be used in an educational setting as a practical demonstration of the Erichsen Cupping Test.

Product Definition

The selected research project involves the design and build of a table top sheet metal dome tester. This tester will be used in The University of Akron's undergraduate manufacturing lab and will be a practical demonstration of the Erichsen Cupping Test. The purpose of this tester is to use a dome to deform a piece of sheet metal and be able to qualitatively examine the stampability properties of a sheet metal piece. This will be accomplished by using a dome-shaped piston to apply an increasing force to the sheet metal test piece until it fails. Additionally, a fixture with an upper and lower die will be used to secure the test piece. The fixture will contain a ring such that when a clamping load is applied to the fixture the ring will secure the test piece. A variable clamping load will be used to secure the sheet metal piece which will allow for alteration in the stretching and drawing of the piece.

The dome tester must adequately secure the test piece by providing a clamping load that can be varied as desired. The dome tester should deform a 4 inch by 4 inch sheet metal test piece by applying an increasing load until failure of the test piece. The piston that deforms the test piece must have a hemispherical dome head. The dome tester should be safe to use and operate and all pieces designed should be able to be moved by one person for ease of use. The budget for the tester is $500, though cost should be minimized when possible.

Principles of Operation

The force required to deform a piece of sheet metal is called the forming force. The forming force equation is as follows:

$$F = \frac{(Y_s + UTS)}{2} \cdot A_c \qquad \text{eq. 1}$$

where Y_s is the material yield strength, *UTS* is the ultimate tensile strength of the material, and A_c is the cross sectional area of the workpiece (Cooper). Because the dome testing is a continuous process, the average force between yield strength and ultimate tensile strength is used as an estimate (Schey p. 307). This concept is displayed in Figure 3.

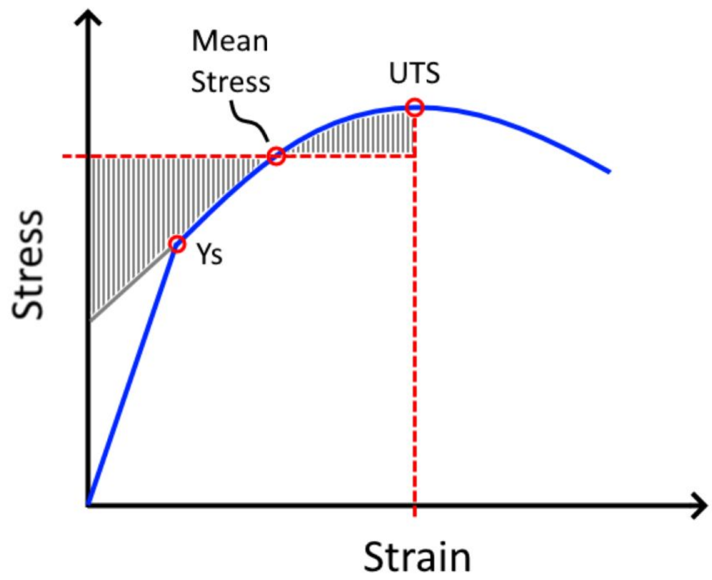

Figure 3: Mean Stress on a Stress-Strain Curve

Another important concept to consider is the clamping force, or how hard the upper and lower dies are pressing together to hold the sheet metal in place. If only a small amount of clamping force is applied, the sheet metal sample will slip as the press moves downward and a draw will occur. If a more rigorous clamping force is applied, the sheet metal will be fixed in place and only be able to stretch. By focusing on stretching for calculation purposes, the group can account for the maximum amount of clamping force required to use the machine. The clamping force calculations are shown in the Detail Design Section.

Conceptual Design

Initially, a vulcanizer that the machining lab already possessed was going to be used to apply the forming force to the sheet metal test piece. A vulcanizer is a machine that uses hydraulics and heat to create molds. The machine was not supposed to be altered or taken apart in any way. Ideas were generated but a simple, cost effective solution was not found.

Alternate solutions to the source of the forming force were brainstormed. It was determined that hydraulic force was to be used as the devices are usually relatively small and can apply large loads of various magnitude. Various car jacks, and hydraulic presses were investigated. The hydraulic press was favorable as it came with a stand to place the workpiece and was still reasonably priced. It was decided that two plates would be used as the clamping solution. Each plate would have a through hole that would allow the dome piston to pass fully through the plates and the test piece in between. In order to hold the test piece and provide a uniform, predictable clamping area, it was decided a protruding ring would be used to clamp the test material. Many design ideas were discussed for the ring that would contact the test piece. A couple ideas proposed were machining down a plate to create an exposed ring, a weld bead ring, and rectangular stock welded into a hexagon. The weld bead design idea was rejected as it would likely wear with repeated use and the hexagon made up of rectangular stock was rejected as any ring that was not perfectly round would have adverse effects to the drawing and stretching of the test piece observed by pulling unevenly. The possible sources of clamping force discussed were hydraulics, clamps, and bolts. Hydraulics was rejected as it was expensive and added an unnecessary level of complication to the design. The clamps were rejected as it would be challenging to vary the clamping force and achieve the required clamping force.

The proposed ideas were discussed with Dr. Gopal, a materials expert, and Steve Gerbetz, the UA Senior Engineering Technician. Each design was reviewed for functionality, safety, ability to machine in-house, cost, simplicity, and ease of use. A general design for the dies and clamping mechanism were then decided upon.

Embodiment Design

The resolved general design was to use a hydraulic press for the forming force source and to machine a top and bottom die from two plates and a piston from a rod. Two raw slabs of steel, about 6" x 6" x 1" each, will be machined. The bottom die will have a through hole in the center of the plate and will be machined away such that a ring with a circular profile will protrude from the flat surface of the die. The top die will also have a through hole in the center of the plate and will have a machined groove that will mate with the ring of the bottom die. The circular ring will serve to crimp and hold the test blank in place. The design concept for the top and bottom dies are shown in Figure 4.

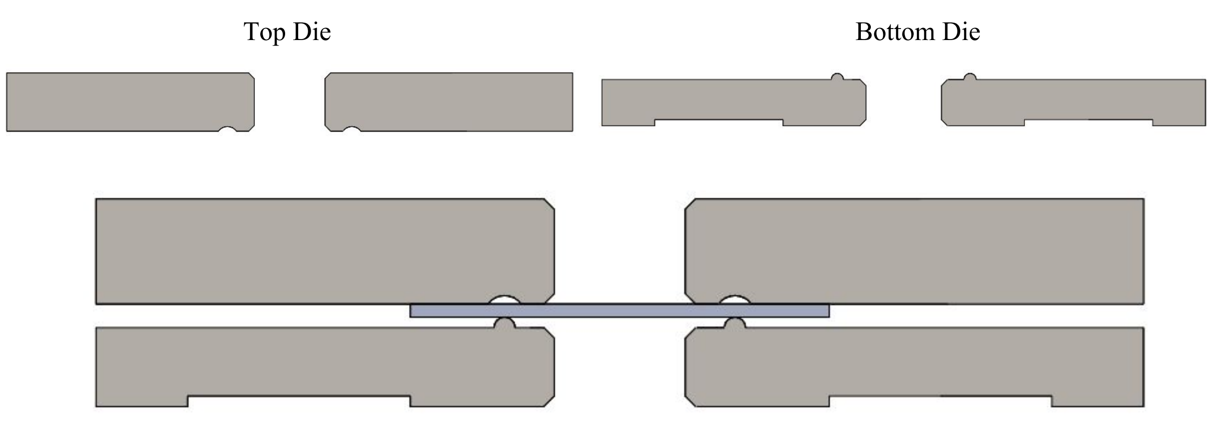

Figure 4: Top and Bottom Die

The size of all the features depend heavily on the forming force required to deform the sheet metal test piece. The forming force was calculated for several common materials that would likely be tested. Calculations were done for 1020 Steel, 6061 T6 Aluminum, and 2024 T3 Aluminum, all with a thickness of .1250 inches. Calculations for these materials are shown in Table 1. The 1020 Steel had the largest calculated forming force of approximately 26,700 lbs or 13.4 tons. Using this force a hydraulic shop press was selected. Hydraulic shop presses are usually sold as a 10, 12, or 20 ton variant. To meet the forming force requirements and allow enough margin for material and press variability, a 20 ton press was chosen. The 20 ton press selected (which can be viewed in Figure A1 in the appendix) has a free-standing frame and does not fit on a table top. However, this was not a strict requirement for the design, as there is enough space in the existing manufacturing lab for the press to fit.

Table 1: Forming Force Calculations

Inputs (1020 Steel)		
	Value	**Units**
Yeild Strength	413.9922	MPa
Ulitmate Tensile Strength	524.0151	MPa
Workpiece Diameter	1.0000	in
Workpiece Thickness	0.1250	in
Results		
F = ((*YS* + *UTS*) / 2) * A		
	Value	**Units**
Cross-Sectional Area	**0.00025**	m^2
Forming Force	**118,824**	N
Forming Force	**26,713**	lbf

Inputs (6061 T6 Al)		
	Value	**Units**
Yeild Strength	236.6966	MPa
Ulitmate Tensile Strength	297.8784	MPa
Workpiece Diameter	1.0000	in
Workpiece Thickness	0.1250	in
Results		
F = ((*YS* + *UTS*) / 2) * A		
	Value	**Units**
Cross-Sectional Area	**0.00025**	m^2
Forming Force	**67,718**	N
Forming Force	**15,224**	lbf

Inputs (2024 T3 Al)		
	Value	**Units**
Yeild Strength	261.5215	MPa
Ulitmate Tensile Strength	454.3171	MPa
Workpiece Diameter	1.0000	in
Workpiece Thickness	0.1250	in
Results		
F = ((*YS* + *UTS*) / 2) * A		
	Value	**Units**
Cross-Sectional Area	**0.00025**	m^2
Forming Force	**90,680**	N
Forming Force	**20,386**	lbf

For the clamping mechanism, a ring of 8 bolts will be used to clamp the sheet metal test blank in the top and bottom die. The ring of bolts will be positioned outside the perimeter of the test sample to simplify assembly. Multiple bolts are being used in order to evenly distribute the clamping load over the entire test sample. The press that was selected for the project has a flat ended, cylindrical ram rod used in the pressing action. In order to achieve the dome shape required for the formability testing, further modifications are needed to be made. Some hydraulic presses have a threaded end and different sized rods that can be interchanged. One possible solution involved creating a custom threaded ram rod with a dome-shaped end. However, the selected hydraulic press does not have a threaded end. Instead, a simple thumb screw and adapter will be used to secure a dome to the existing ram rod. A steel cylinder with a 6" diameter, and about 6" tall, will be machined down to create the modification. The dome adapter will be designed such that the load path is through the piston. This load path simplifies the design and mitigates risks of stress concentrations at the point of intersection of the piston attachment collar and the dome piston. The design concept for the piston dome attachment is shown in Figure 5.

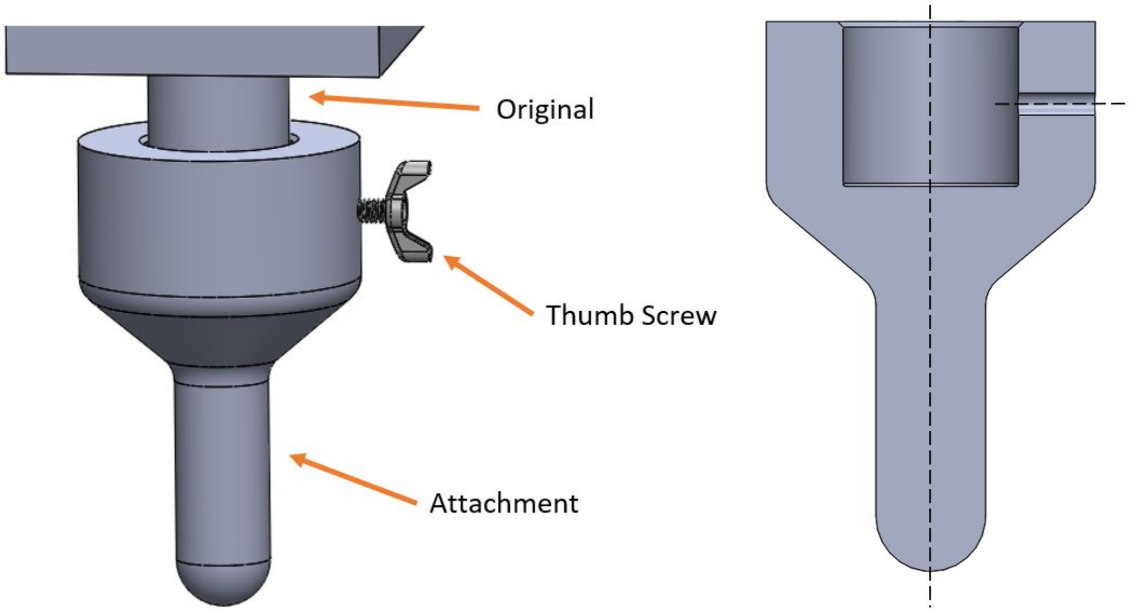

Figure 5: Thumb Screw Dome Adaptor

Possible modes of failure of this design were speculated and considered to determine if there are any flaws in the proposed design. One mode of failure of the bottom die is the ring wears and no longer provides adequate crimping of the test piece. This risk will be mitigated by making the ring fairly pronounced and leaving enough material thickness in the plate such that the ring could be remachined if absolutely necessary. Another failure mode of the bottom die is the bolts clamping the plates together causes the plate to deform. This risk is mitigated by leaving a large amount of material left in the plate therefore increasing the plate stiffness. Another failure mode is bolt fatigue or nut failure from repeated tightening. This failure mode can be mitigated by using large bolts and not torquing to the maximum limit of the bolt. Bolt failure, however, is likely to occur after many uses. Bolts are fairly inexpensive and replacement bolts will be factored into the cost of the design. Another failure mode is the wearing of the dome adapter after repeated use. The material selected for the dome is much stronger than the selected material for the test pieces so this likely won't be an issue. Another failure mode is the shop press test platform failing due to the load of the test setup. The shop press will not be used at maximum capacity. The difference in the load required from the maximum load is much higher than the estimated weight of the test setup.

Detail Design

Once the embodiment design of the dome tester was completed, detailed drawings and calculations were performed to polish the design and make it ready for manufacturing. Final drawings can be found in the Appendix.

Bolts

The bolts size selection was based on the required clamping force to hold the test piece in place without any slipping. The force required to clamp the test piece is very challenging to calculate. The clamping mechanism consists of a ring of eight bolts and a ring and groove that will crimp the test piece. The clamping capability of the bolts is simple to calculate but the effect of the ring and groove on the clamping force is much more challenging to quantify. The bolt selected was a ½-13 Grade 8 per A354 BD. This specification requires the minimum proof strength to be 120 ksi. Assuming the usable stress is ¾ the proof strength, the clamping load is calculated by multiplying .75 by the proof load and the tensile stress area of the bolt. The calculated clamping load is 14.4 ksi or 7.2 tons. The eight bolts therefore provide a maximum clamping load of 115.3 ksi or 57.6 tons. This clamping capability of the bolts is significantly higher than the required forming force of 13.36 tons. This was done to mitigate any risk of insufficient clamping as the required clamping force is very challenging to quantify. The bolt clamping calculations are found in Table 2.

Table 2: Bolt Clamping Load Calculation

Clamping Load Calculations			
Description	**Symbol**	**Value**	**Units**
Tensile Strength		150	ksi
Proof Strength		120	ksi
Tensile Stress Area	At	0.1599	in^2
Clamping Load per Bolt	P	14.391	ksi
"		7.1955	ton

Top and Bottom Dies

The material selected for the top die, bottom die and the dome adapter was 4140 Steel Alloy. This material was selected because of its material properties, specifically its high yield strength. The top and bottom die are very similar. Both are made from 1” thick plates. Thick plates were used to increase the stiffness of the setup and eliminate the possibility that the plates would deform due to the bolts clamping load or the applied force on the test piece. Additionally, both plates have a center hole of 1.25 inches with a chamfer on both sides of the hole. This hole size provides ample clearance to the dome piston and test material that must pass through it and allows for misalignment in the stroke path and machining tolerances of the piston. Both the top and bottom die have a bolt circle of eight 33/64” through holes which allows clearance for the clamping bolts. The bolt circle is large enough such that a 4” by 4” test piece can be nested inside the circle. Additionally the bolt circle is positioned such that 4 bolts will pass through the hydraulic press stand beams. This positioning was used to keep the source of clamping load as close to the test piece as possible, to safely secure the plates during operation, and to minimize the size of the plates therefore reducing weight. The bolt circle was to be machined by mating the ring and groove of the bottom and top die then clamping them together to minimize misalignment. The holes through the press stand beams are to be machined last after all other parts are machined and aligned to reduce misalignment errors. The bottom die has a protruding ring and the top die has a recessed groove. When mated, the clearance between the ring and groove is less than that of the thickness of the test material. This gap allows for adequate clamping while not over pinching the material, which would create a stress concentration resulting in failure of the test material at the ring as opposed to the desired failure at the dome piston location. The bottom die also has two wide recesses along the bottom of the plate which mate to the press stand beams. This is a safety feature which is intended to keep the plates from sliding off the stand during assembly and disassembly. The recesses are larger than the beams to allow for alignment adjustments.

Dome Adapter

The dome adapter attaches to the press piston using a thumb screw. The length of the selected thumb screw is longer than the material thickness of the dome to allow for adequate engagement with the press head. The press head mating hole is only slightly larger than the press head to allow for a tolerance fit but not so large as to create misalignment issues. When fully assembled, the dome adapter is nested inside the assembled dies. This creates challenges for assembly and operation. Because the dome is nested in the die the dies must be assembled to the press stand platform at a lower rung of the press stand and moved up to the dome adapter. This action requires two people which is not desirable. This design decision was made because the press only has a stroke length of 2.0” and if the adapter was outside of the assembled dies the stroke length would not be sufficient to engage the test material. A redesign that would allow one person to use and operate would have been much more complex and costly. It was decided that in order to cut cost, ease of use would have to be compromised. Additionally, for safety, tests should be run with two individuals in case of error or injury.

Assembly and Operation

For safety, all assembly, disassembly and testing should be done with at least two people. To assemble the dies and adapter to the press, the press stand beams must first be lowered one notch on either side. Place the bottom die on the press stand beams; make sure the beams of the press stand are mated with the recesses underneath the bottom die. Lay the sheet metal test piece on the bottom die, resting inside the bolt ring. Next, place the top die onto the test piece and the bottom die. Carefully line up the bolt holes using the edge of the dies as rough guides. Use the bolts, washers and nuts to secure the top and bottom die to the press stand. Reference the Dome Test Assembly (Figure A5) for the order and orientation of the bolts, nuts and washers. Hand snug the bolts in a star pattern. Using a wrench tighten the bolts, once again in a star pattern, to the desired angle of turn based on the type of test being run. The angle of turn should never exceed 34 degrees beyond hang snug. This angle of turn limit was calculated using the bolt proof stress and stiffness and is shown in Table 3. Using an angle of turn larger than 34 degrees beyond hand snug risks bolt failure.

Table 3: Bolt Angle of Turn Calculations

Angle of Turn Calculations				
Description	**Symbol**	**Value**	**Units**	**Notes**
Bolt Elastic Modulus	E	3.00E+07	psi	
Bolt Pitch	p	0.077	in	
Washer Thickness	t	0.062	in	PN 90107A033
Nut Thickness	H	0.438	in	PN 90499A033
Major Diameter Area	Ad	0.500	in	
Tensile Stress Area	At	0.1599	in^2	
Fastener Length	L	3.000	in	
Threaded Length	Lt	1.469	in	PN 91257A724
Length of Threaded Portion in Grip	lt	1.531	in	
Length of Unthreaded Portion in Grip	ld	0.905	in	
Fastener Stiffness	kb	2.63E+06		
Turn		0.0710	turns	
"		25.56	deg	

Once the bolts are tightened, assemble the dome adapter to the press piston using the thumb screw. Next, using two people, raise the press stand beams up one notch on each side at the same time. Do not raise one side of the beams up at a time as the dome adapter will collide with the top die and not line up in the hole correctly. Now that the dies and adapter have been assembled the hydraulic press can be ratcheted until the desired result is achieved. An assembly and operation checklist is in the Appendix.

Manufacturing

Manufacturing was completed in the UA engineering machine shops with the help of technician Aaron Trexler. Two different machines were required to complete the manufacturing of all components. The Clausing manual lathe was used for the machining of the dome adapter. The cylindrical nature of the component design lends itself well to the lathe, which works by spinning the part before contact is made with a tool. As such, machining the dome adapter was fairly straightforward. The raw material obtained was a 4140 round stock. The procedure was to take off small amounts of material on multiple passes until the desired outer dimension was obtained. The adapter hole was then drilled. The designed specification of a flat bottom required an extra step, which involved reaming the remaining material after the initial drilled hole. After this, the remaining excess material on the dome end was removed on the lathe. Because this was a manual machine, close attention to each movement was required to ensure excess material was not wrongly removed.

The dies required a more complex setup. These parts were manufactured on a Haas CNC machine. The raw material procured were two large plates, which required extensive machining. In addition to the required mating surfaces and drilled holes, both plates had to be substantially reduced in thickness. (Note: the plates were donated to the team and were larger than spec.) The lathe was not able to be used for this operation due to the width of the parts. This meant that a program had to be written for the CNC machine. While this wound up producing a very nice part in the end, there were difficulties involved. While the machine was capable of cutting the steel, reducing the plate thickness required substantial cutting. The particular machine used is really optimized for aluminum components. This meant that cutting such large quantities of high-grade steel required an excessive amount of time. Due to this, the design was re-evaluated, and it was determined that increasing the thickness of the dies (in effect, reducing the machining time) would have negligible effects on component function.

Figure 6: Machining the rods (left) and plate (right)

Discussion

After manufacturing, the intention was to assemble the dies and conduct testing on several sheet metal test pieces. Unfortunately, due to unforeseen circumstances, the project was not able to be finished as intended. The through holes in the press stand beams need to be machined, the press needs to be bolted into the ground, the parts need assembled and the press needs to be tested.

Had we completed the assembly we would have tested the press on multiple sheet metal test pieces, making any alterations necessary. The design would then have been evaluated for flaws or improvements.

Conclusion

Despite the challenges the group faced, most of the design project was able to be finished by the end of the semester and under budget. Unfortunately, the dome tester was not able to be completely checked or fine tuned like originally planned. The project began on the basis of the Erichsen Cupping test and was expanded from there. Similar tests already exist commercially but the team strived to create a small-scale test that can be used in the classroom setting.

A key component of a senior design project is its effects on the students’ academic experience. A senior project should build on the knowledge and experience gained during the previous college career, while challenging the team. One unique element to the project is how it ties into manufacturing principles. Unlike most coursework, this project aims to not only design, but also produce a functioning product. This entailed learning how to communicate and talk with manufacturers as well as how to create custom parts in-house.

By collaborating with faculty members the conceptual design was completed, taking into account factors such as ease of use, safety, and machinability. With this in mind early conceptual sketches of the final product were created before moving into the detailed design. The design of the dome tester would take advantage of an off-the-shelf hydraulic press and custom machined parts. An upper and lower die, featuring a mating crimp-ring and a dome-shaped ram rod adapter were fabricated. In order to make sure all of the materials would function as intended, a detailed design and calculations were conducted. Forming force calculations were completed to verify the required deformation load and clamping force calculations were done in order to size appropriate bolts.

This design project allowed the participating students to function in a diverse team and create a schedule while working towards a deadline. Tasks were separated based on individual strengths and availability. Working together and providing updates at weekly meetings was a key component to success, which is something that can be applied to future career endeavours. The dome tester can be used as a learning tool for engineers at the University of Akron for many years to come.

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Appendix

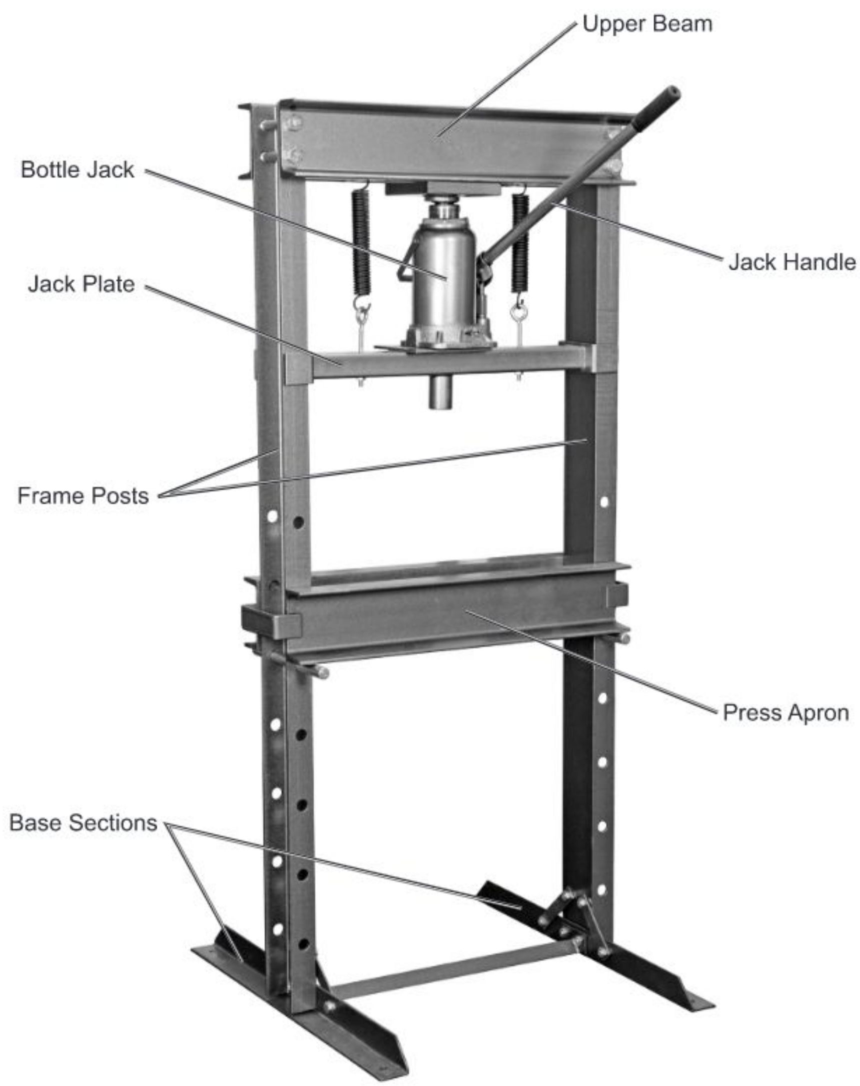


Figure A1: Central Machinery 20T Shop Press SKU 60603

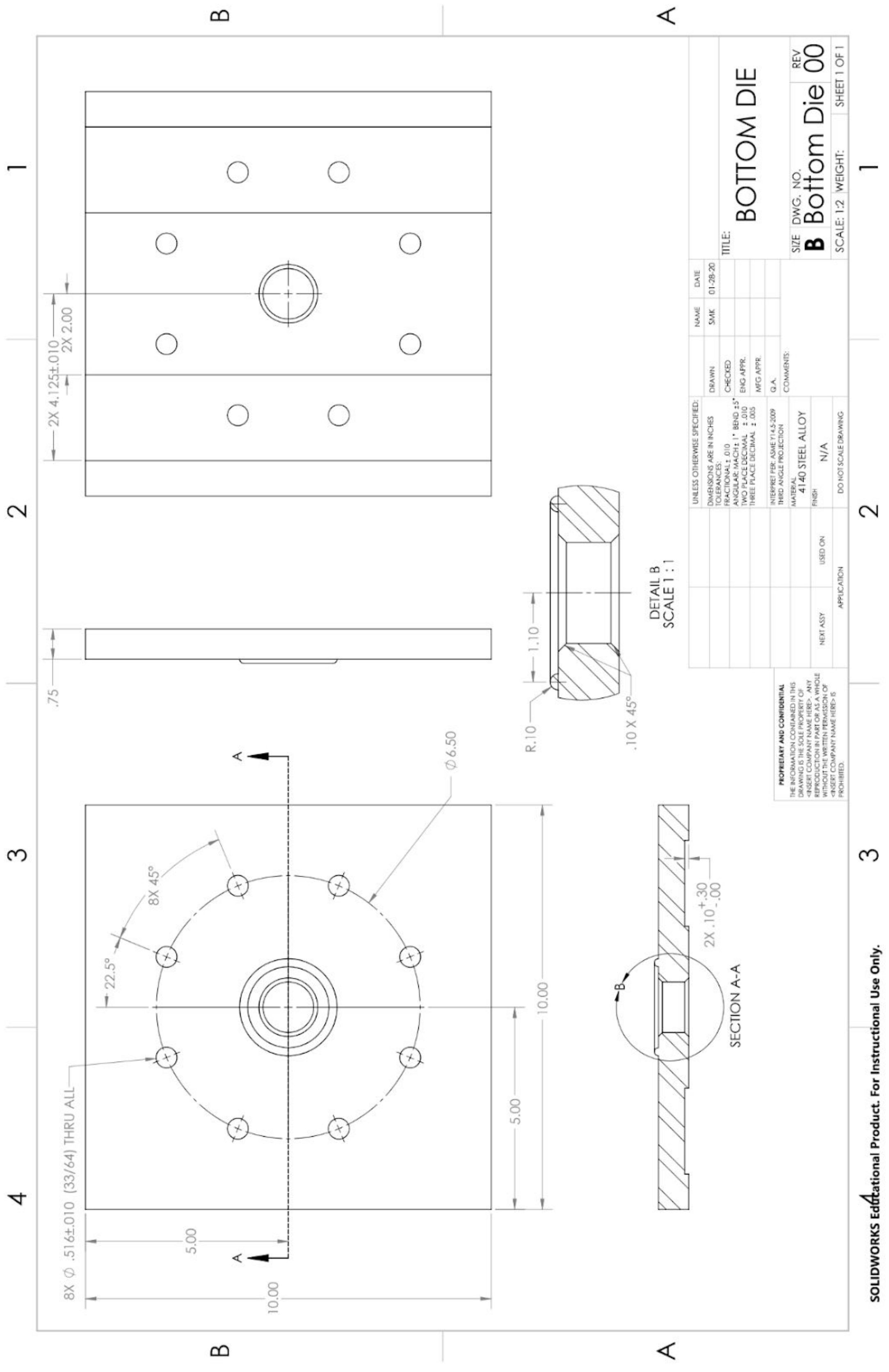


Figure A2: Bottom Die CAD Drawing

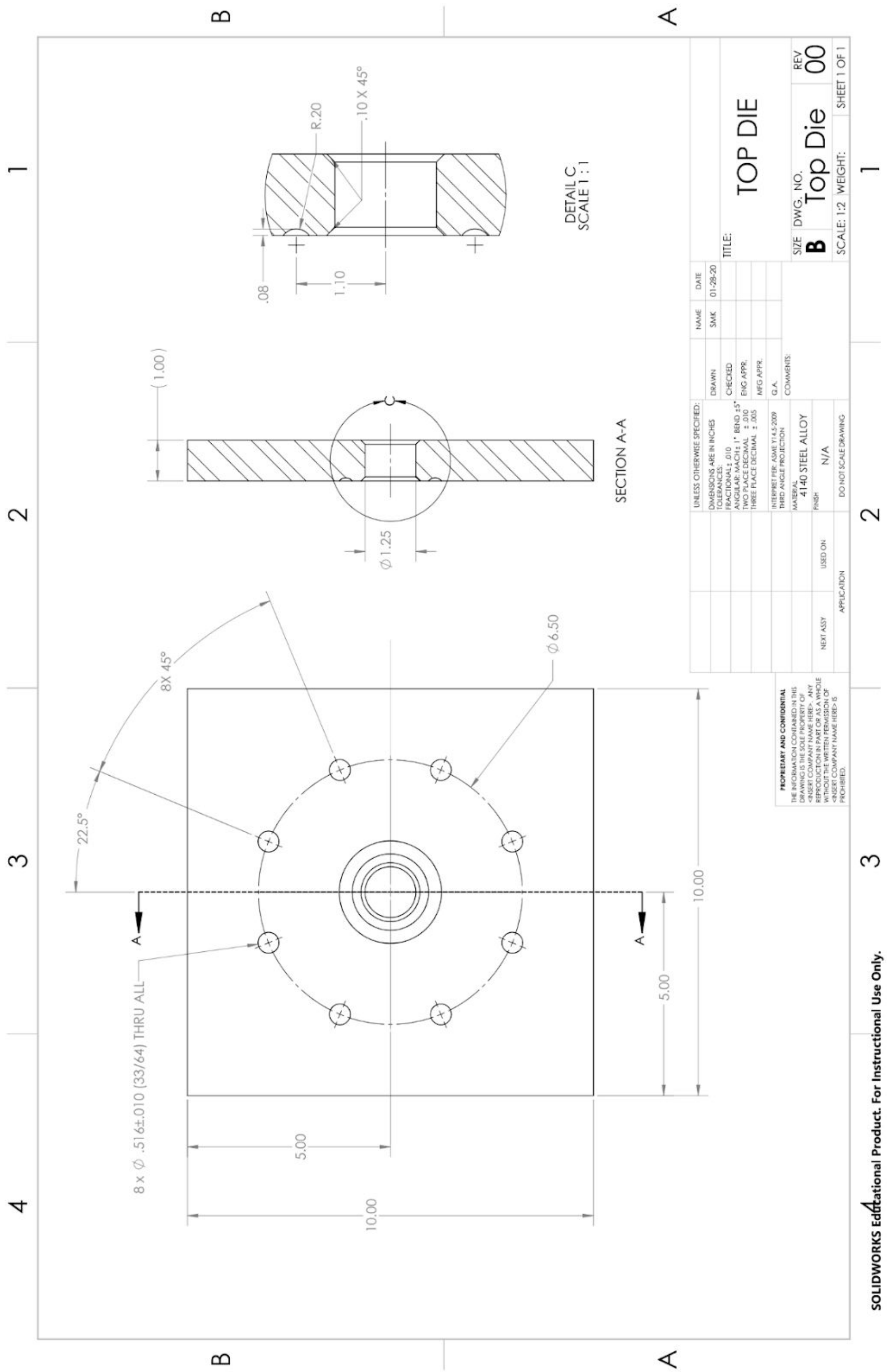


Figure A3: Top Die CAD Drawing

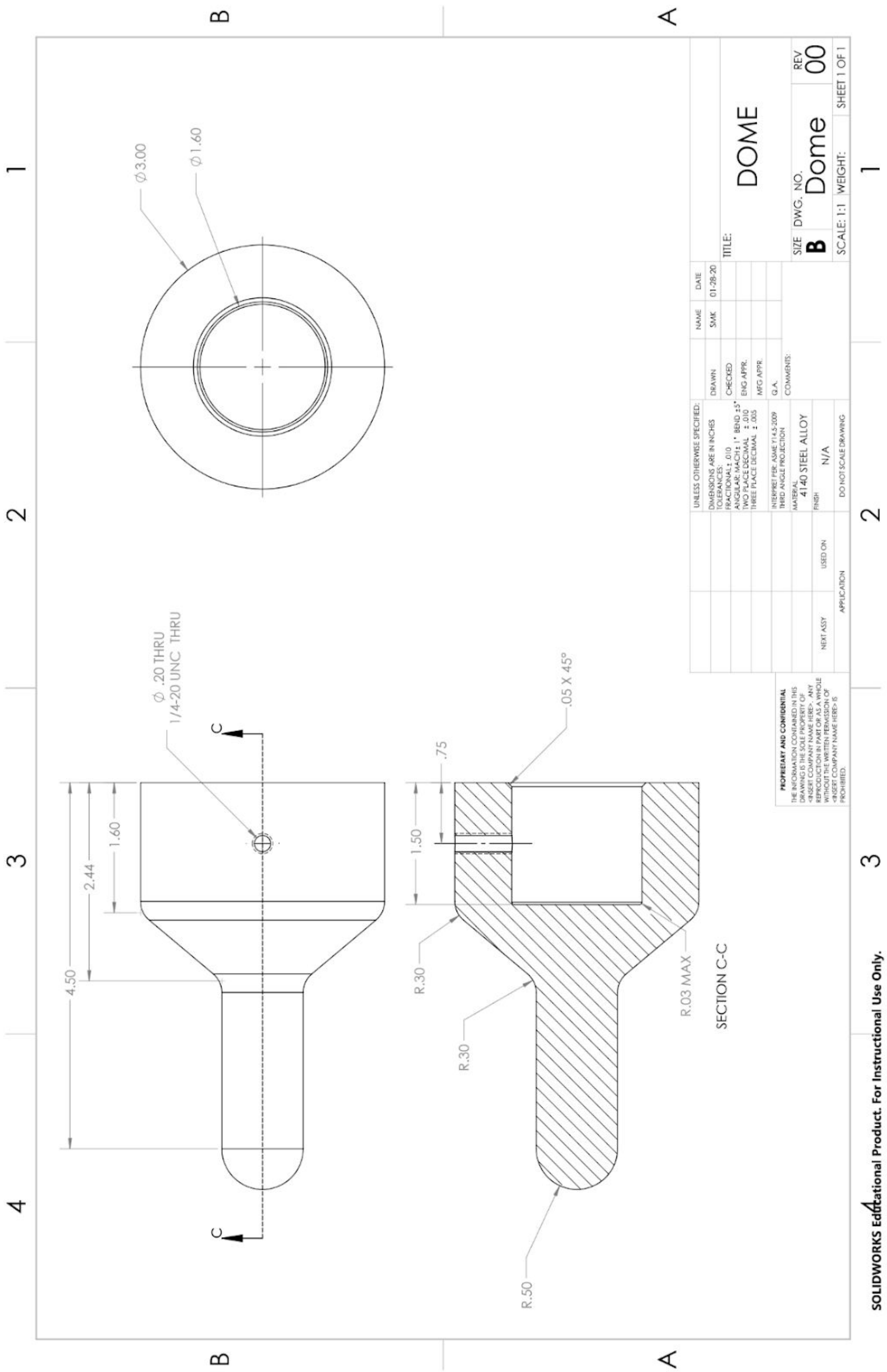


Figure A4: Dome / Ram Rod CAD Drawing

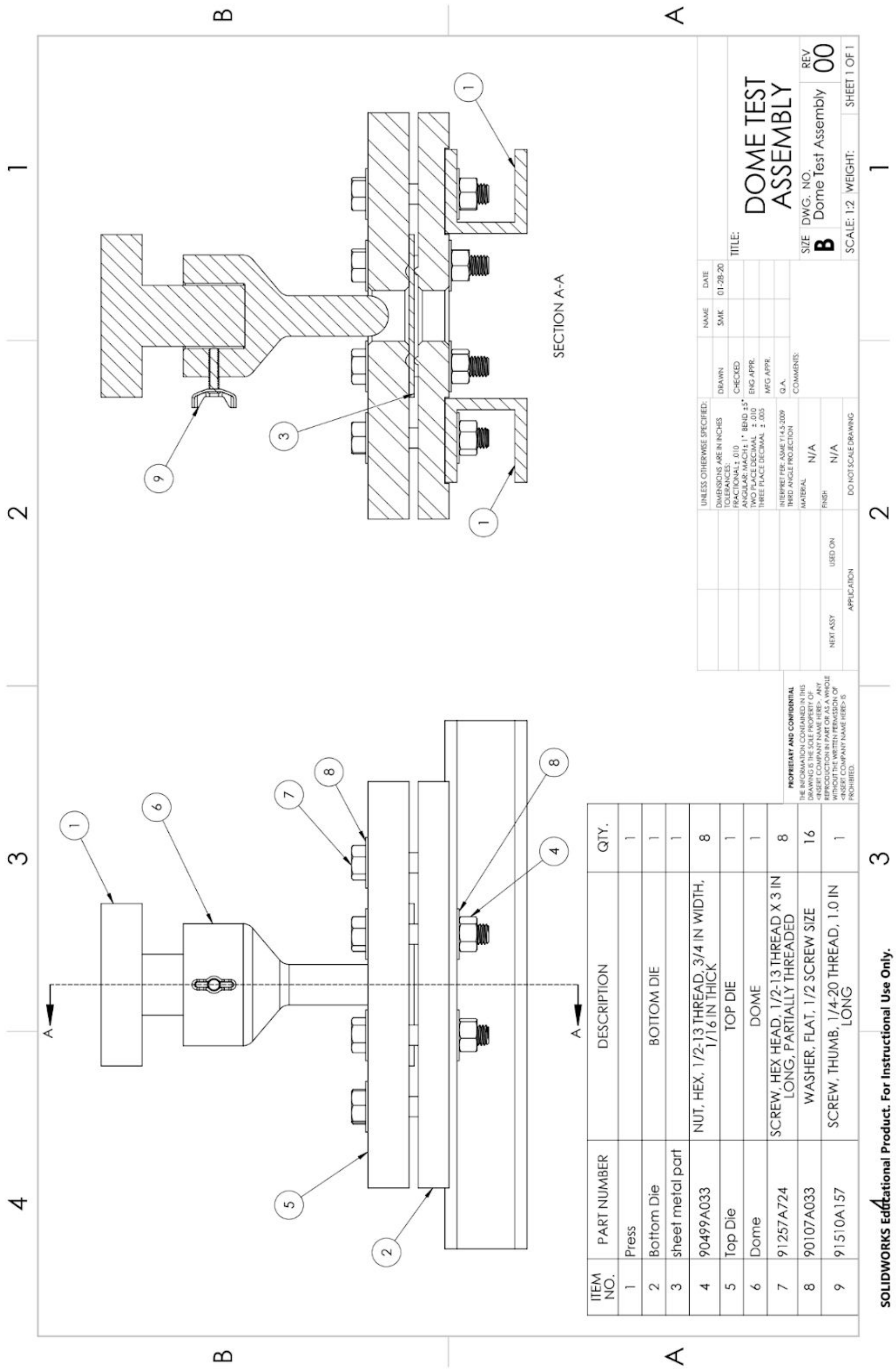
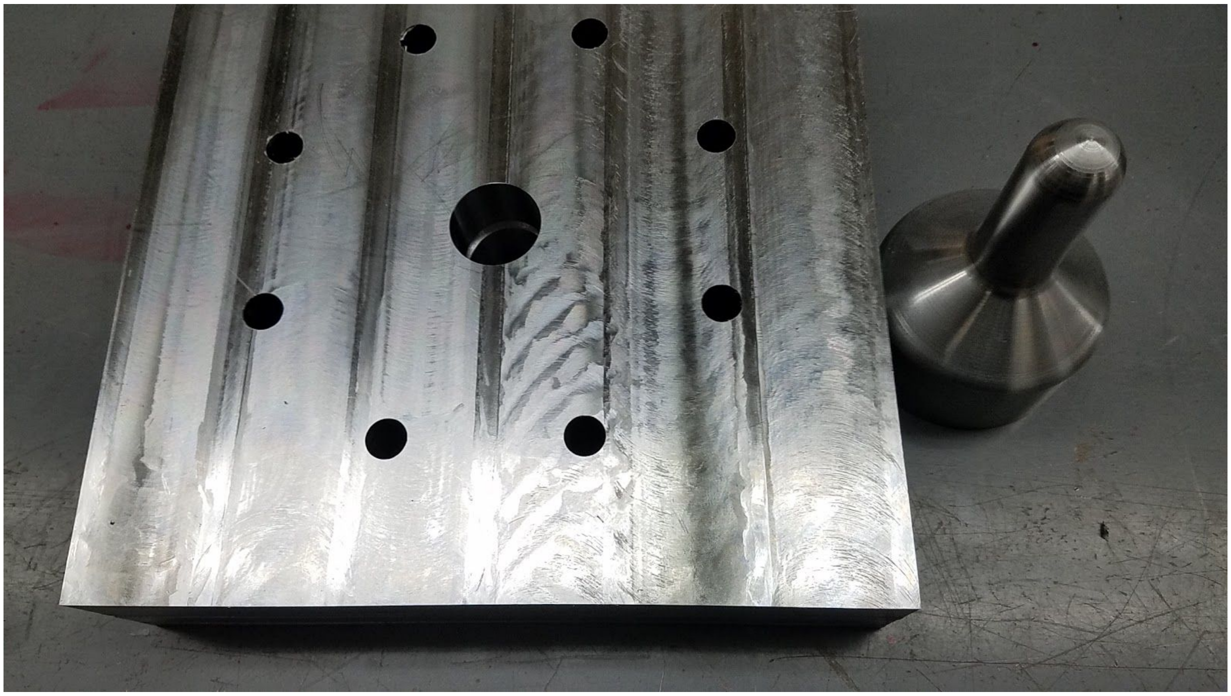
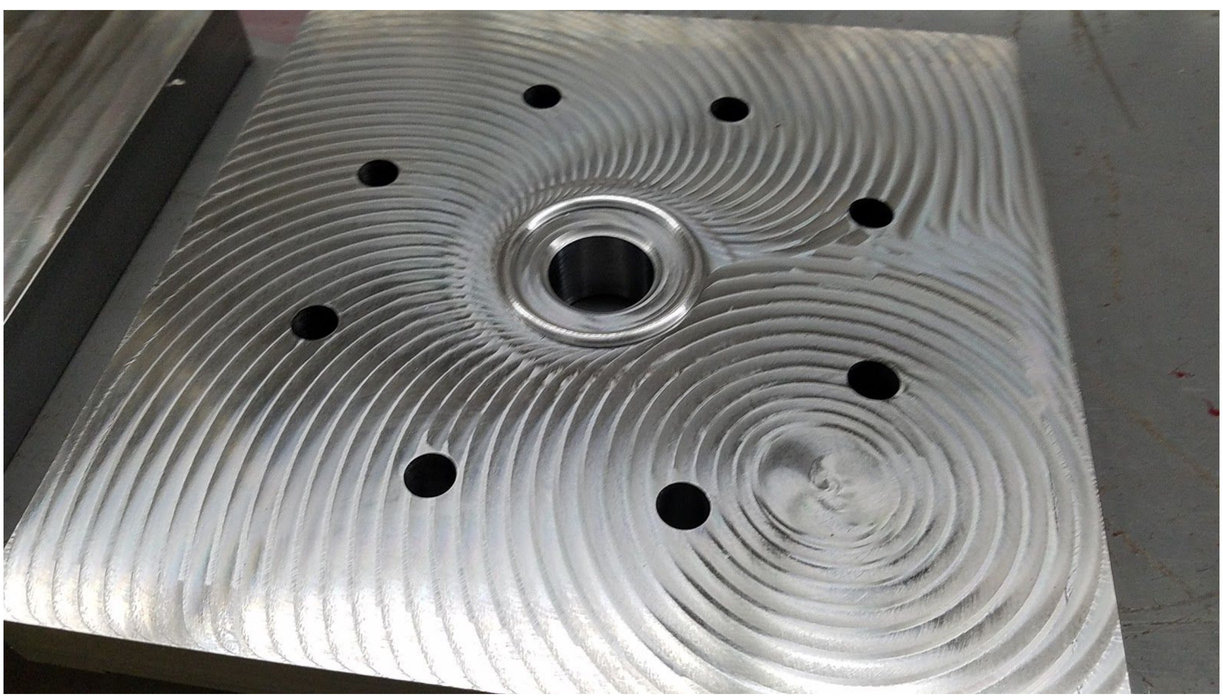


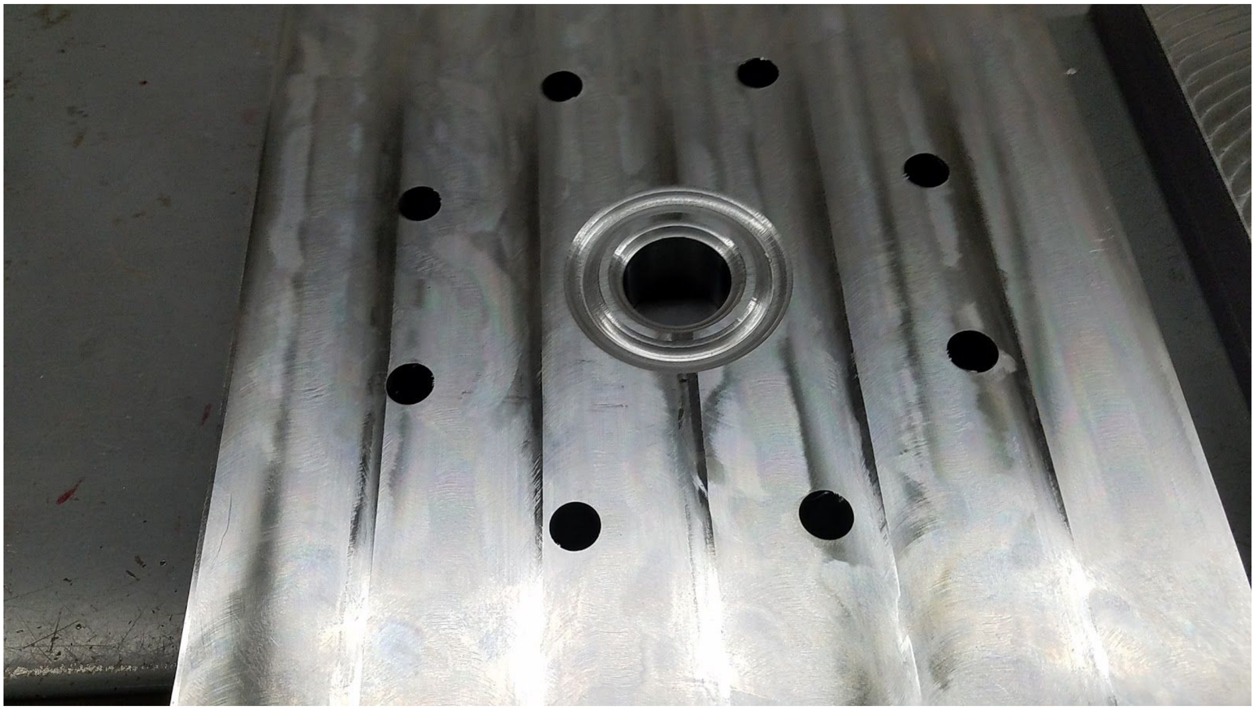
Figure A5: Complete Assembly CAD Drawing



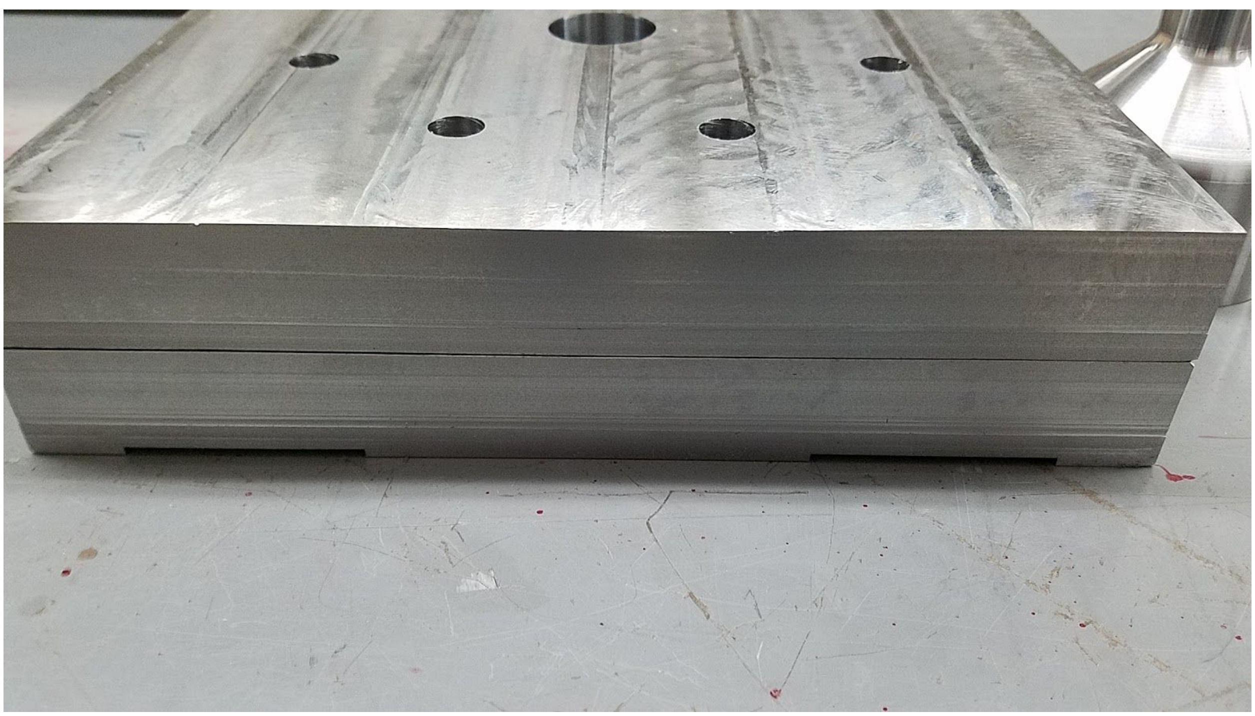
Figures A6: Machined clamping dies (together) and dome adaptor



Figures A7: Final machined bottom die



Figures A8: Final machined top die



Figures A9: Side view of top and bottom die pressed together

Assembly and Operation Checklist

Steps require at least two people. Safety glasses should be worn at all times.

1. Lower press stand center beam one notch on each side
2. Place the bottom die on the press stand. Ensure notches on bottom die mate with press stand beams
3. Lay sheet metal test piece on bottom die nested inside bolt ring
4. Place the top die on top of the test piece and bottom die lining up the bolt holes of the top and bottom dies.
5. Use the bolts, washers and nuts to secure the top and bottom die to the press stand. Reference Figure A5 for hardware assembly order. HAND TIGHTEN in a star pattern.
6. Using a wrench, tighten bolts in a star pattern to the desired angle of turn. The angle of turn should NEVER exceed 34 degrees beyond hand snug.
7. Assemble dome adapter to press piston using thumb screw.
8. Using two people, raise the press stand beams up one notch on either side AT THE SAME TIME. Do NOT raise one side up at a time. This could result in dome piston damage.
9. Ratchet hydraulic press until desired result is achieved.
10. Release the pressure in the hydraulic press before disassembly. DO NOT leave the hydraulic press unattended with pressure remaining in the press.