Swagelok's Hand Tube Bender

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Swagelok Hand Tube Bender Project

Senior Design/Honors Project
Fall 2016 – Spring 2017

Technical Sponsor: Joe Rodriguez
Project Advisor: Dr. Shao Wang

Team Members:
Tyler Brown (Honors)
Chapin Hutama (Honors)
Seth Bills
William McConnell
1. **Abstract**

In our project, we are assigned to develop a hand tube bender that is able to bend medium, high pressure, and standard 1/4” and 3/8” tubing. The bender also shall be capable of being used with two hands without the aid of a bench vise and have provisions for use in a bench vise for convenience. The bender shall not damage the tube during bending and induce a maximum of 8% ovality in the bent tubing. In addition, the cost of the bender shall be less than the existing hand tube bender and be resistant to rusting from ordinary use.

The first step of our plan is to develop our conceptual designs by brainstorming and analyzing the function structure diagram of the hand tube bender in order to give us an idea how the bender works. Moreover, we created an objective tree to fulfill the expected needs of both customers and the manufacturer. We also developed our morphological chart based on our function solutions from function structure diagram and created four different possible designs for our project. Each design that we developed will be used in the weighted design matrix with specific criteria we developed in our objective tree so that we are able to choose the best design that is most suitable for our criteria. After selecting a single design, we will continue our project by developing our embodiment design. In our embodiment design, we start to add our design with the detailed layout of functions and connecting methods. We will also calculate the force and give an estimated cost for our bender so that we could calculate the total cost to produce the bender.

In the second part of our project, we continued our plan by selecting a material for all components of our design. The materials chosen are based on their ability to fulfill the requirements of the project. After which we developed our prototype design in 3D CAD software in order to have a visual model that we can validate and improve upon. We continued our project by manufacturing prototypes and testing them. We performed three distinctive tests for validation of our prototypes. A bending test was performed to measure the ovality of the bent tubing and the maximum torque to bend. Secondly we tested the strength of the benders by attempting to bend hardened drill rod. Finally, a salt spray test was performed to validate the corrosion resistance of the benders.
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2. EXECUTIVE SUMMARY

2.1. Introduction
A tube bender is a tool used to permanently deform tubing at a desired radius and angle. A hand tube bender is typically a cold forming process that is limited to a maximum bend angle of a 180°. Hand tube benders have many factors to consider such as required input force, reliability, ovality, and not damaging the tube surface. In addition, part of our design strategy for this hand tube bender project is to minimize the hand force required to bend the tube.

There are many methods of hand tube benders that already exist such as ram type, roller type, and rotary draw bending type. Ram type bending is the simplest and cheapest method of bending tube. The ram type bender works by restraining the tube at two external points, and then the ram advances on the central axis which deforms the tube. The roller type bender works by using two or three rollers that apply pressure to the tube gradually changing the bend radius. The other type is rotary draw bending, this method is very advanced and has high precision as a result. This method is very popular for bending tube.

The main task of this project was to design a hand tube bender to replace Swagelok’s current high pressure hand tube bender. The project was open ended with the new design criteria based on cost, tubing size, type of tubing, durability, tube damage, and functionality. The new design(s) has to be able to bend both 1/4” and 3/8” standard, medium, and high pressure tubing. The design also has to have the capability of bending tube just by hand and through the aid of a vise. The design also has to bend tube with an ovality less than 8% and, be corrosion resistant. Also, the new design has to cost less than the current Hand tube bender design.

3. PRODUCT DEFINITION

3.1 Simple Design Brief
A hand tube bender is used to bend tubing to a desired bend radius. Moreover, the bender shall be capable of bending standard, medium, and high pressure tubing while keeping the ovality below 8%.
The hand tube bender needs to be able to bend medium, high pressure and standard ¼” and 3/8” tubing. The bender should be capable of being used with two hands and leave no damage to the tubing. In addition, the bender should induce minimal ovality in the bent tubing. The bender also needs to be resistant to rusting from ordinary handling.

In order to bend tube, it’s important to understand different process to bend tube. Draw, press, ram, and roll bending are the methods that can be considered. Moreover, bending principles such as elongation and bend radius will intersect in several ways that influence the effectiveness of tube bending. Controlling physical deformation is important for creating a smooth rounded bend to not effect flow in the tube.

The primary needs from customers are less force to bend, low cost, durable, and accurate in results. In some industries, it is also important to consider the speed of bending. Possible markets would include companies that manufacture valves and fittings and the customers of these manufacturing companies.

<table>
<thead>
<tr>
<th>No</th>
<th>Requirements</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>New design shall be capable of bending medium, high pressure, and standard ¼” and 3/8” tubing.</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>The bender shall be capable of being used with two hands without the aid of a bench wise</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>The bender shall have provisions for use in a bench vise for convenience</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>The bender shall not damage the tube</td>
<td>4</td>
</tr>
</tbody>
</table>
The bender shall induce minimal ovality in the bent tubing (8%) during bending.

The cost of the bender shall be less than the current hand tube bender design.

The bender shall be resistant to rusting from ordinary handling/use.

<table>
<thead>
<tr>
<th></th>
<th>Requirement</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>The bender shall induce minimal ovality in the bent tubing (8%)</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>The cost of the bender shall be less than the current hand tube bender design</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>The bender shall be resistant to rusting from ordinary handling/use</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1: Requirements

## 4. Conceptual Design

### 4.1 Initial Brainstorming

![Conceptual Designs_1](image)

Figure 2: Conceptual Design
In our initial brainstorming (Figure 2), we researched the existing bending methods that could be applicable in our design such as ram type, roll type, compression type, and rotation or draw type bending methods. Moreover, we continued our design by brainstorming and focusing on compression type bending methods.

Figure 3: Conceptual Design

In Figure 3, we created the compression type bending with a connecting link. This design is built by considering the force that could be applied to bend a tube. By adding a connecting link from handle to the housing, we believed it would reduce the force and increased the moment to bend the tube. After further analysis, it was found that this method would not be a suitable design because it did not decrease the required input force.

Furthermore, the next design was a ratchet method. This design was built by considering the required force to bend a tube. This design allowed us to give a continuous linear or rotary force in only one direction to bend the tube. The ratchet would be consisting of gear and pawls inside the bender die. In addition, the purpose of this design idea was to reduce the amount of force applied to bend the tube with a minimal movement from hand.
## 4.2 Solutions

<table>
<thead>
<tr>
<th>No</th>
<th>Solution</th>
<th>Analysis of Solution</th>
<th>Yes /No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ram Type Bending</td>
<td>less expensive, high ovality rate, fast in bending</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Hydraulic Force</td>
<td>high cost in maintenance and manufacturing, less force applied, relative easy to use</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Gear Mechanism</td>
<td>expensive, less force applied, high cost in manufacturing</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Electrical (Battery)</td>
<td>High cost in maintenance and manufacturing, less force applied, relative easy to use</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Ratchet</td>
<td>Reduce the huge amount of force, high cost in maintenance, impractical to use</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>Rollers</td>
<td>Less ovality, should have bench vise, good for high volume</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>Compression Type</td>
<td>Ideal for hand tube bender, good for low volume, simple to assembly</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>Electromagnetic Force</td>
<td>Less hand force applied, expensive, impractical to use</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>Linkage method</td>
<td>Impractical to use, does not reduce hand force significantly</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2: Solutions
4.3 Function Structure Diagram

In our design, the block diagram in Figure 4 describes how the hand tube bender was applied. Moreover, in Figure 5, we expanded our block diagram into a function structure diagram to determine the force and method that was applied in our design. In our function structure diagram, we had a tube as our material flow and hand force as our energy flow in order to bend the tube.

Figure 4: Block Diagram

Figure 5: Function Structure Diagram
4.4 Objective Tree

The objective tree above was created based on the expected needs of both customers and manufacturers. Our design showed that functionality, cost, and design time are considerations in our goal of designing a hand tube bender.

Moreover, cost such as repair cost, material cost, and manufacturing cost need to be considered in our design. We believed that repair cost has a lower value compared to material cost and manufacturing cost due to the possibility for the customer to repair the tools. In addition, the process of manufacturing is the most important aspect in our cost consideration to lower the overall cost of the tool.

The functionality aspect is most important in our design. Durability such as corrosion resistance and wear resistance (daily use) are considered in our design because having good durability can increase the lifespan of a tool. Corrosion resistance has a larger value than wear resistance (daily use) due to the fact the hand tube bender requires friction between the bender die and tube. Moreover, our team agreed that ergonomics such as ease of tube insert/removal, ease of bending tube (force), tube clamping, and usability are factors that we would like to implement in our design.
Ovality, tube surface damage, and accuracy of bend angle are quality aspects that we are going to aim for. Our design has a maximum allowable ovality of 8%. In addition, the accuracy of the bend needs to be considered by our team due to the spring back that occurs at the end of bending.

In the safety category, FMEA becomes a consideration. We listed the possible failures and their likelihood to occur in our design to lower the potential hazards that could occur during bending.

4.5 Morphological Chart

<table>
<thead>
<tr>
<th>Sub Function</th>
<th>Function Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilization</td>
<td><img src="image1" alt="Stabilization" /></td>
</tr>
<tr>
<td>Rotation Bending Method</td>
<td><img src="image2" alt="Rotation Bending" /></td>
</tr>
<tr>
<td>Tube Removal</td>
<td><img src="image3" alt="Tube Removal" /></td>
</tr>
</tbody>
</table>

Table 3: Morphological Chart
DESIGN 1 (Modified Hand Tube Bender)

In our design 1, we made a design similar to the Swagelok MS-HTB tube benders. By using the same materials and certain components from MS-HTB product line, we are able to reduce the cost. We also improved our bender die and handle, so that will be suitable in bending high pressure tube. Moreover, we maintained the simplicity in this bender in order to deliver a direct force from hand force to the tube. Simplicity is one of best advantages in this design. By keeping the design similar to MS-HTB, we would like to maintain the uniqueness of the hand tube bender as it would fit in perfectly with the current Swagelok product line. The design would feature longer handles than the current hand tube bender design which would decrease input force. This design would feature the same tube bender groove that the MS-HTB benders have to minimize ovalization.
In this design, our team agreed to design a single hand tube bender that would be capable of bending two different size tubing. The idea was to reduce the number of tube benders a customer may need. The design philosophy was to keep the design simple and resemble Swagelok’s MS-HTB tube bender. We also improved the handle and housing in order to bend two different size high pressure tubes. The Double Barrel concept would maintain the same tube groove geometry that the MS-HTB products have therefore the ovality would be minimized. However, in this design, we found that it would require a latch that is suitable to hold 2 tubes at the same time.
Our next design is a Geared bender. The idea of this bender is to use a gear mechanism to create a mechanical advantage to greatly reduce the input force. In this design, we are using 3 gears and a roller housing. We also used a ratchet mechanism in the handle that would be able to give a linear hand force in the handle. Furthermore, the design has advantages such as reduced input force and minimal ovalization. By using 2 small rollers, we are able to reduce the ovality in the tube. However, cost and complexity are the major problems in this design.
The 4th design is the ratchet bender. In this design, we were using a ratchet rack and pinion to deliver a compression force to the tube. The bender die for both sides have 2 different size for ¼” and 3/8” tubes. The ovality of the tube became our concern in this design. However, the design is able to significantly reduce the force needed to bend a tube. By using ratchet mechanism, the compression force will increase with a minimal hand force applied. Moreover, the design is focusing on the effectiveness to bend tubing within a specified time. This design is suitable in tube and fitting industries that require a fast bending process.
Table 4: Weighted Design Matrix.

In table 4, we calculated our four designs in a weighted design matrix, so that we could choose the best design that is most suitable based on our criteria. We found that the 1st and 2nd designs (Modified design and Double Barrel) had a close total score. It was because both of these designs were acceptable and the differences that could be considered in these two designs were cost and ovality. After calculating our cost, the 2nd design (Double Barrel) has a lower cost score compared to the modified one that affected our design matrix score.

On the other hand, the Geared Bender and Ratchet Bender had a lower total score compared to the previous two. It happened because the cost that we calculated was much higher compared to the Double Barrel and Modified design. Moreover, we agreed that the Ratchet Bender has a low ovality score that reduces the score significantly compared to the other designs. It was mainly because of the compression method applied in our design affects the ovality that we would like to minimize.
5 Embodiment Design

5.1 Detailed Layout of Functions and Connecting Methods

Figure 11: Layout and Connections for 1/4” bender

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stainless Bender Die</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>SS 4 Link Machined</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>SS Clevis Machined</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>3/8” Machining Plate</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>ASSY Solid Short Handle</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>ASSY Solid Long Handle</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>3/8” Curved Pin</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>3/8” x 3/8” Shoulder Screw</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>Spring Washer (5/8”)</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>Spring Washer</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Stainless Roller Support</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>Flared Roller Die</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>1/4” Dowel</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>Latch Screws</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>3/8” Handle Grip</td>
<td>2</td>
</tr>
</tbody>
</table>

*SOLD AND ITALICIZED COMPONENTS ARE NOT PRE-EXISTING*
In figure 11 and 12, we created the layout of functions in order to see every component in our design. The connecting method that we used are bolts and pins with varying sizes.

5.2 Embodiment Rules and Principles

The rules of Clarity, Simplicity, and Safety are applicable in our design. For Clarity aspect, we have a role for each component in the design. Moreover, Simplicity aspect in our design can be seen by maintaining the previous material and roller housing in our design. Furthermore, the principle of Force Transmission is also applied in our four designs. The designs have a single force movement either from top to bottom or left to right so that the direction of force will not change. It was important for our design to have Division of Task principles because we assigned a single function to a specific part. Therefore, it allows us to further explore each component to decrease an unambiguous behavior in our design.
5.3 Calculations

![Figure 13: Current hand tube bender design-0° Free Body Diagram](image)

Current hand tube bender design-0°

\[ \sum F_x = 0 \]
\[ F_{input} + R_x = 0 \]
\[ R_x = -F_{input} = -\frac{M_0}{d_2 + d_3} \]
\[ \sum F_y = 0 \rightarrow R_y = 0 \]
\[ CCW(+) M_A = 0 \rightarrow -F_{input}(d_2 + d_3) + M_0 = 0 \]
\[ F_{input} = \frac{M_0}{d_2 + d_3} \rightarrow F_{input,MAX} = \frac{M_{0,MAX}}{15.78} \]
Figure 14: Current hand tube bender design-90° Free Body Diagram

Current hand tube bender design-90°

\[
\sum F_x = 0 \rightarrow R_x = 0
\]

\[
\sum F_y = 0 \rightarrow R_y - F_{input} = 0
\]

\[
R_y = F_{input} = \frac{M_0}{d_1 + d_2 + d_4}
\]

\[
CCW(+)\sum M_0 = 0 \rightarrow M_0 - F_{input}(d_1 + d_2 + d_4) = 0
\]

\[
F_{input} = \frac{M_0}{d_1 + d_2 + d_4}
\]

\[
\sum F_x = 0 \rightarrow R_x + F_{input} \cos(\theta) = 0
\]

\[
\sum F_y = 0 \rightarrow R_y - F_{input} \sin(\theta) = 0
\]
\[ CCW(+) \sum M_0 = 0 \]

\[ M_0 - F_{input} \cos(\theta)(d_1 + d_4 \cos(\theta) + d_3 \cos(\theta)) - F_{input} \sin(\theta)(d_2 \sin(\theta) + d_3 \sin(\theta)) = 0 \]

\[ F_{input} = \frac{M_0}{d_1 \cos(\theta) + d_4 \cos^2(\theta) + d_3 \cos^2(\theta) + d_2 \sin^2(\theta) + d_3 \sin^2(\theta)} \]

Graph 1: Hand Tube Bender Force Input Comparison Graph

Graph 1 shows a comparison between the input force required from the current Swagelok hand tube bender and our design for both 1/4” and 3/8” high pressure tubing. It is evident from this graph that the required input force for the new design is less than the input force required from the current hand tube bender for both size tubing. This was not a requirement imposed by Swagelok but we considered reducing input force from the beginning of the project as well as included it in our decision matrix when selecting which conceptual design should be pursued further.
Figure 15: Roller Force Free Body Diagram

Graph 2: Tube Bender Caster Die Force Comparison Graph
Graph 3: Tube Bender Caster Die Force Comparison Graph
Figure 16: Force Input Calculations – MS-HTB Modified
### Table 5: Cost Calculation for MS-HTB-4 (Modified) Design

<table>
<thead>
<tr>
<th>Material Number</th>
<th>Quantity</th>
<th>Description</th>
<th>Estimated Cost</th>
<th>Cost Correction Factor</th>
<th>Updated Cost Estimation</th>
<th>Cost Doubled</th>
<th>Cost Tripled</th>
</tr>
</thead>
<tbody>
<tr>
<td>2811-189</td>
<td>1</td>
<td>STAINLESS ROLL SUPPORT</td>
<td>$7.33</td>
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<td></td>
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<tr>
<td>2811-185</td>
<td>1</td>
<td>SS 6 Clevis Machined</td>
<td>$7.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2811-191</td>
<td>1</td>
<td>SS 6T Latch Machined</td>
<td>$9.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2093-496</td>
<td>1</td>
<td>3/8&quot; CLEVIS PIN</td>
<td>$0.36</td>
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<tr>
<td>2093-489</td>
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<td>1/4&quot; LOK DOWEL</td>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>ASSY - SOLID LONG HA</td>
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<tr>
<td>2093-499</td>
<td>1</td>
<td>-6T NAMEPLATE ONE PIECE</td>
<td>$0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2084-565</td>
<td>2</td>
<td>3/8 X 7/8 SHOULDER SCREW</td>
<td>$0.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2085-106</td>
<td>1</td>
<td>SPRING WASHER (LG)</td>
<td>$0.03</td>
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<td></td>
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<tr>
<td>2812-441</td>
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<td>HTB POCKET MANUAL</td>
<td>$0.42</td>
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<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$113.46</strong></td>
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<td></td>
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</tr>
</tbody>
</table>

### Table 6: Cost Calculation for MS-HTB-6 (Modified) Design

<table>
<thead>
<tr>
<th>Material Number</th>
<th>Quantity</th>
<th>Description</th>
<th>Estimated Cost</th>
<th>Cost Correction Factor</th>
<th>Updated Cost Estimation</th>
<th>Cost Doubled</th>
<th>Cost Tripled</th>
</tr>
</thead>
<tbody>
<tr>
<td>2812-193</td>
<td>1</td>
<td>STAINLESS ROLL SUPPORT</td>
<td>$48.96</td>
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</tr>
<tr>
<td>2811-195</td>
<td>1</td>
<td>SS 8 Clevis Machined</td>
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<tr>
<td>2093-508</td>
<td>1</td>
<td>1/2&quot; CLEVIS PIN</td>
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<tr>
<td>2093-506</td>
<td>2</td>
<td>LOK DOWEL</td>
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<td>2811-196</td>
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<td>SS 8 Latch Machined</td>
<td>$7.22</td>
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<tr>
<td>2093-501</td>
<td>1</td>
<td>LATCH SCREW</td>
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<tr>
<td>2093-503</td>
<td>1</td>
<td>ASSY - SS LONG HANDLE</td>
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<td>2093-502</td>
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<td>ASSY - SS SHORT HANDLE</td>
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<tr>
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<td>-8 NAMEPLATE ONE PIECE</td>
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<tr>
<td>2085-364</td>
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<td>SHOULDER SCREW</td>
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<tr>
<td>2085-053</td>
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<td>SPRING WASHER (LG)</td>
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<td>SPRING WASHER (LG)</td>
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</table>
Table 7: Cost Calculation for Double Barrel Design

<table>
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<tr>
<th>Quantity</th>
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<th>Estimated Cost</th>
<th>Cost Correction Factor</th>
<th>Updated Cost Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ROLL DIE, PLATED</td>
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<tr>
<td>1</td>
<td>LEAD ROLLER, PLATED</td>
<td>$6.31</td>
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<tr>
<td>2</td>
<td>ROLL DIE, PLATED</td>
<td>$7.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1/4&quot; CLEVIS PIN</td>
<td>$0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3/16&quot; LOK DOWEL</td>
<td>$0.49</td>
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<tr>
<td>1</td>
<td>3/8&quot; CLEVIS PIN</td>
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<td></td>
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<tr>
<td>2</td>
<td>1/4&quot; LOK DOWEL</td>
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</tr>
<tr>
<td>1</td>
<td>SS 3/16 Link Machined</td>
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<tr>
<td>1</td>
<td>SS Latch Machined</td>
<td>$20.00</td>
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<td>1</td>
<td>LATCH SCREW</td>
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<td>1</td>
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<tr>
<td>1</td>
<td>ASSY - SOLID SHORT H</td>
<td>$4.47</td>
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<tr>
<td>1</td>
<td>NAMEPLATE</td>
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<tr>
<td>2</td>
<td>SHOULDER SCREW</td>
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<tr>
<td>2</td>
<td>SPRING WASHER (LG)</td>
<td>$0.06</td>
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<td>1</td>
<td>SPRING WASHER</td>
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<tr>
<td>1</td>
<td>HTB POCKET MANUAL</td>
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<td></td>
<td><strong>Total</strong></td>
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Table 8: Cost Calculation for Geared Bender Design

<table>
<thead>
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<th>Part Number</th>
<th>Quantity</th>
<th>Description</th>
<th>Estimated Cost</th>
<th>Cost Correction Factor</th>
<th>Updated Cost Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bender Die Housing (Top)</td>
<td>1</td>
<td>$14.09</td>
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<td></td>
</tr>
<tr>
<td>1 Bender Die Housing (bottom)</td>
<td>1</td>
<td>$6.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Main Driving Gear (60 teeth)</td>
<td>1</td>
<td>$33.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Small Driving gear (18 teeth)</td>
<td>1</td>
<td>$19.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Driven gear (18 teeth)</td>
<td>1</td>
<td>$19.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Machined Link</td>
<td>2</td>
<td>$5.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Roller Housing</td>
<td>1</td>
<td>$6.28</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1 ROLL DIE, PLATED</td>
<td>1</td>
<td>$4.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Driving pawl</td>
<td>1</td>
<td>$10.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Reverse Pawl</td>
<td>1</td>
<td>$10.00</td>
<td></td>
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</tr>
<tr>
<td>1 Torsion Spring</td>
<td>1</td>
<td>$5.81</td>
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<tr>
<td>1 SS Latch Machined</td>
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<td>$7.33</td>
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</tr>
<tr>
<td>1 ASSY - SOLID LONG HA</td>
<td>1</td>
<td>$4.74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 ASSY - SOLID SHORT H</td>
<td>1</td>
<td>$4.47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$152.44</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the tables above, we calculated the cost for each design. This was accomplished by using SolidWorks costing Add-In software to analyze the geometry of each of the components for each bender assembly. By running already existing components through this software and then comparing the estimated cost to the true cost provided from Swagelok, a correction factor was able to be obtained for each component. The components from each of the conceptual designs, with the exception of the Ratchet Bender, was then also analyzed with this software. By using the correction factors and applying them to similar conceptual design components an estimated cost was obtained for each of the bender designs.

6 Test and Result

6.1 Material Selections

We used Finite Element Analysis (FEA) Software that allows us to construct, refine, and optimize our design before prototypes were manufactured. By using FEA analysis on every part of our hand tube benders (size ¼” and 3/8” tubing) (See Appendix 10.2), we were able to determine our material selections that would meet the necessary requirements.

Higher corrosion resistance, ductility, strength, hardness, and toughness are factors that become our consideration in our material selections for the bender die and link components of hand tube bender. We decided to use a Copper-Nickel-Chromium alloy for our bender die, latch, roller housing, and link of our hand tube bender that has a high ultimate tensile strength (UTS) (approximately 160 ksi) depending on the heat treatment. In addition, 10-15% Chromium in the stainless steel alloy also helps our bender to be resistant to rust. Moreover, for our handle, we used stainless steel as our material with a calculated length so that it can reduce the input force for bending. Finally, our roller uses heat treated alloy steel that has approximately 95 ksi UTS which provides enough strength and hardness properties that meet the required specifications. Making the rollers from a material other than stainless steel will help reduce the chance of galling from occurring.

6.2 Manufacturing

The manufacturing process for our design was a variation of the existing manufacturing process of the current MS-HTB tube benders. The variation of the process included changing the heat treatment of the bender die as well as the steps between the casting and machining processes. The main reason for these changes was to fulfill the corrosion resistance requirement of the project.

Early in the design phase of our selected conceptual design, our team decided that both the bender die and link would be made from castings. The main contributing factor to this decision was the cost of producing these parts, which have rather complex geometry. It was more cost
effective to go the casting route rather than have these components machined from billet. Our design of this high-pressure hand tube bender calls for these two components to be cast and then have critical features machined to specifications, we however were unsure if we would be able to follow our intended manufacturing process while investigating how to prototype our bender designs. Fortunately, additive manufacturing made this possible. By having the die castings of the bender die and link 3D printed from wax we were able to follow our intended manufacturing process while not having to have investment die castings produced. By having the die castings 3D printed this also reduced potentially long lead times from other manufacturing methods. After castings were produced the bender die and link components were machined to our specifications. The manufacturing process for the roller dies remained the same as the MS-HTB bender rollers.

![Figure 17: MS-HTB-IPT-4-001-SS casting](image17.png)

![Figure 18: MS-HTB-IPT-4-003-SS casting](image18.png)

![Figure 19: MS-HTB-IPT-6-001-SS casting](image19.png)
During our manufacturing process a number of challenges arose that needed to be resolved in order to get prototypes made. Lead times for getting quotes on components was not originally considered when our timeline was created, as a result we fell a number of weeks behind on our manufacturing. Fortunately, with the help of a number of Swagelok associates we were able to overcome these supplier challenges and have our designs prototyped with a couple of weeks still left to test and analyze. This has been a good learning experience since none of us had ever prototyped anything to this degree before. In future projects, additional lead time will be added to the manufacturing process to avoid falling behind schedule.

6.3 Test

For our test plan, we are testing our bender by bending standard, medium, and high pressure tubes with different size tubing (1/4” and 3/8”) at 15°, 90°, 165°, and 180° angle then calculating the ovality:

\[
\text{Ovality} \% = \frac{\text{Max OD} - \text{Min OD}}{\text{Nominal OD}} \times 100
\]

In addition, we continued our test to find a safety factor of our bender by attempting to bend a drill rod. We are bending the drill rod (figure 22) in order to find the peak torque and calculate our safety factor:
Factor of Safety = \( \frac{\text{Actual Breaking Strength (lb)}}{\text{Normal Working Load (lb)}} \)

Figure 22: Bending the Drill Rod

Furthermore, we performed a salt spray test on our bender, which is an accelerated way to determine if the surface of the components will rust later in life. Results of this test are intended to validate our material selections and confirm they meet the oxidation specifications.

### 6.4 Result and Analysis

<table>
<thead>
<tr>
<th>Material/PN</th>
<th>Tube Size</th>
<th>15° Ovality</th>
<th>90° Ovality</th>
<th>165° Ovality</th>
<th>180° Ovality</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS-T4FK-095-20-S</td>
<td>0.25</td>
<td>1.40</td>
<td>0.80</td>
<td>1.80</td>
<td>2.00</td>
</tr>
<tr>
<td>SS-T4FK-095-20-S</td>
<td>0.25</td>
<td>0.60</td>
<td>1.00</td>
<td>0.80</td>
<td>1.20</td>
</tr>
<tr>
<td>SS-T6FK-S-134-20-S</td>
<td>0.375</td>
<td>0.93</td>
<td>1.33</td>
<td>1.07</td>
<td>1.07</td>
</tr>
<tr>
<td>SS-T6FK-S-134-20-S</td>
<td>0.375</td>
<td>1.07</td>
<td>N/A</td>
<td>N/A</td>
<td>1.07</td>
</tr>
<tr>
<td>SS-T6FK-S-134-20-S</td>
<td>0.375</td>
<td>0.93</td>
<td>1.33</td>
<td>1.07</td>
<td>1.07</td>
</tr>
<tr>
<td>SS-T6FK-SH-083-20-S</td>
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<td>2.27</td>
<td>N/A</td>
<td>N/A</td>
<td>2.40</td>
</tr>
</tbody>
</table>

Table 9: Medium Pressure Tube Test

For medium pressure tubing, we tested ¼” and 3/8” tubing. However, due to limitation of 3/8” size tubing, we only managed to bend two tubes for a complete set of angles (15°, 90°, 165°, and 180°) while the rest are only 15° and 180°. Moreover, we measure minimum and maximum outer diameter (OD) in order to calculate ovality:
\[
\text{Ovality} \% = \frac{(\text{Max OD} - \text{Min OD})}{\text{Nominal OD}} \times 100
\]

The table above shows that both size benders successfully bent the medium pressure tubing with an ovality less than 8%.

<table>
<thead>
<tr>
<th>Material/PN</th>
<th>Tube Size</th>
<th>15 Ovality</th>
<th>90 Ovality</th>
<th>165 Ovality</th>
<th>180 Ovality</th>
</tr>
</thead>
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<tr>
<td>SS-483-T-120</td>
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<td>1.00</td>
<td>0.60</td>
<td>0.80</td>
</tr>
<tr>
<td>SS-483-T-120</td>
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<td>1.80</td>
<td>0.60</td>
<td>0.80</td>
<td>1.40</td>
</tr>
<tr>
<td>SS-483-T-120</td>
<td>0.25</td>
<td>1.60</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>SS-483-T-120</td>
<td>0.25</td>
<td>1.00</td>
<td>0.60</td>
<td>0.80</td>
<td>1.20</td>
</tr>
<tr>
<td>SS-483-A-120</td>
<td>0.25</td>
<td>1.20</td>
<td>1.00</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>SS-483-A-120</td>
<td>0.25</td>
<td>1.40</td>
<td>1.20</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>SS-483-A-120</td>
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<td>1.80</td>
<td>0.80</td>
<td>0.80</td>
<td>1.00</td>
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<tr>
<td>SS-483-A-120</td>
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<td>1.20</td>
<td>1.00</td>
<td>0.80</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 10: Hardened (T-120) and Annealed (A-120) High Pressure Tube Test

<table>
<thead>
<tr>
<th>Material/PN</th>
<th>Tube Size</th>
<th>15 Ovality</th>
<th>90 Ovality</th>
<th>165 Ovality</th>
<th>180 Ovality</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS-612-T-120</td>
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<td>1.47</td>
<td>1.60</td>
<td>1.73</td>
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</tr>
<tr>
<td>SS-612-T-120</td>
<td>0.38</td>
<td>1.20</td>
<td>1.60</td>
<td>1.47</td>
<td>1.60</td>
</tr>
<tr>
<td>SS-612-T-120</td>
<td>0.38</td>
<td>1.33</td>
<td>1.60</td>
<td>1.60</td>
<td>0.27</td>
</tr>
<tr>
<td>SS-612-T-120</td>
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<td>1.33</td>
<td>1.60</td>
<td>1.47</td>
<td>1.47</td>
</tr>
<tr>
<td>SS-612-A-120</td>
<td>0.38</td>
<td>1.60</td>
<td>1.60</td>
<td>1.73</td>
<td>1.87</td>
</tr>
<tr>
<td>SS-612-A-120</td>
<td>0.38</td>
<td>1.47</td>
<td>1.73</td>
<td>1.73</td>
<td>1.60</td>
</tr>
<tr>
<td>SS-612-A-120</td>
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<td>-7.33</td>
<td>1.47</td>
<td>1.47</td>
<td>1.60</td>
</tr>
<tr>
<td>SS-612-A-120</td>
<td>0.38</td>
<td>1.33</td>
<td>1.60</td>
<td>1.73</td>
<td>1.60</td>
</tr>
</tbody>
</table>

Table 11: Hardened (T-120) and Annealed (A-120) High Pressure Tube Test

Table 10 shows we bent both hardened and annealed medium and high pressure tubing (size ¼”) respectively and calculated an ovality of less than 2%. Table 11 shows our bender successfully bent 3/8” tube with approximately 2% ovality for hardened and annealed medium and high pressure tubing respectively.

<table>
<thead>
<tr>
<th>Material/PN</th>
<th>Tube Size</th>
<th>15 Ovality</th>
<th>90 Ovality</th>
<th>165 Ovality</th>
<th>180 Ovality</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS-T4-S-035-20-S</td>
<td>0.25</td>
<td>4.00</td>
<td>5.20</td>
<td>1.60</td>
<td>3.60</td>
</tr>
<tr>
<td>SS-T4-S-035-20-S</td>
<td>0.25</td>
<td>3.60</td>
<td>3.00</td>
<td>3.40</td>
<td>2.60</td>
</tr>
<tr>
<td>SS-T4-S-035-20-S</td>
<td>0.25</td>
<td>3.20</td>
<td>3.00</td>
<td>1.20</td>
<td>2.80</td>
</tr>
<tr>
<td>SS-T4-S-035-20-S</td>
<td>0.25</td>
<td>3.40</td>
<td>2.80</td>
<td>3.40</td>
<td>3.40</td>
</tr>
<tr>
<td>SS-T6-S-035-20-S</td>
<td>0.375</td>
<td>2.13</td>
<td>0.93</td>
<td>0.67</td>
<td>1.60</td>
</tr>
<tr>
<td>SS-T6-S-035-20-S</td>
<td>0.375</td>
<td>1.20</td>
<td>0.93</td>
<td>3.07</td>
<td>1.59</td>
</tr>
<tr>
<td>SS-T6-S-035-20-S</td>
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<td>1.87</td>
<td>4.93</td>
<td>4.80</td>
<td>4.00</td>
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<tr>
<td>SS-T6-S-035-20-S</td>
<td>0.375</td>
<td>2.80</td>
<td>4.67</td>
<td>4.27</td>
<td>4.40</td>
</tr>
</tbody>
</table>

Table 12: Standard Tube Test (Size ¼” and ¾”)
For standard tubes, we have a higher ovality result compared to medium and high pressure. However, our bender successfully bent standard tubing with an ovality of less than 8%. (Complete data can be seen in Appendix)

Moreover, our team calculate the benders safety factor by measuring the peak torque that our bend achieved while attempting to bending the drill rod. The ¼” bender measured a peak torque of 1020.2 lb-in. The safety factor can be calculated by the following formula:

$$\text{Factor of Safety} = \frac{\text{Actual Breaking Strength (lb – in)}}{\text{Normal Working Load (lb – in)}}$$

The highest working load achieved while bending high pressure tubing is labeled as “Normal Working Load”

$$\text{Factor of Safety} = \frac{1020.2 (lb – in)}{416.2 (lb – in)}$$

$$\text{Factor of Safety} = 2.451$$

Therefore, the safety factor for the ¼” bender is 2.451.

Again, we calculated the safety factor for the 3/8” bender using with same method. The Actual Breaking Strength that our bender achieved after attempting to bend the drill rod was 3492.2 lb-in. The highest torque achieved while bending 3/8” high pressure tubing is again labeled as “Normal Working Load”.

$$\text{Factor of Safety} = \frac{3492.2 (lb)}{1403.6 (lb)}$$

$$\text{Factor of Safety} = 2.488$$

Therefore, the safety factor for the 3/8” bender is 2.488.

In addition, we also measured the spring-back (see appendix 10.3) of each test specimen. The amount of spring-back varies based on the bend radius, bend angle, wall thickness, and tubing material.
We attempted to bend drill rod to determine the strength of our bender and it can be seen from figure 23 that the latch did not move. However, there is always room for improvement in our design. In figure 24, the shoulder screw that connects the link and roller housing yielded for the 3/8” bender. With either a better material selection for the shoulder screw or by counter boring the link component, the maximum yield strength of the overall bender assembly would be improved. Note that the ¼” link was counter bored and experienced no visible yielding after the ultimate strength test was performed.
In the figure 25, we performed tests on the current hand tube bender design prior to developing conceptual designs as a reference. This information was then compared to our prototype for the following: galling, latch movement, spring-back, and ovality. As we can see, there is a significant difference between the nominal OD and OD after the tube is bent by the current hand tube
bender design compared to our prototype. From figure 26 it can be seen that the tube visually maintains its form.

Moreover, in figure 27, the result of the current hand tube bender design shows marks on the tube due to a combination of friction between the tube and the caster die. There is also a scratch due to the movement of latch that is not fastened properly.

Figure 27: Current hand tube bender design’s Result

Figure 28: MS-HTB’s (Prototype) Result
The result of latch force from our prototype bender can be seen in figure 28. This bender showed no movement while bending that would result in a scratch to the tube.

In addition, we also tested our material selections by performing a salt spray test on our prototype. The salt spray test is an accelerated way of determining whether the bender components are likely to develop surface rust later in life. Figure 29 shows our prototype before salt spray test and the result can be seen in figure 30 and 31.
Figure 30: Prototype After Salt Spray Test by Swagelok
CONCLUSIONS
- After 2 hours of salt spray exposure, there were multiple areas that experienced corrosion.
- The rollers and pins experienced moderate corrosion.

ADDITIONAL INFORMATION
ASTM B 117: Standard Practice for Operating Salt Spray (Fog) Apparatus
Total Test Time: 2 hours
Chamber Temperature: 95°F ± 2°F or - 3°F
NaCl (salt) Concentration: 5%

<table>
<thead>
<tr>
<th>Date</th>
<th>Chamber Temperature (F)</th>
<th>Elapsed Time (Hrs)</th>
<th>Interruptions</th>
<th>Volume of Collected Solution (mL)</th>
<th>Specific Gravity</th>
<th>pH</th>
<th>Temp @ pH meas. (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/10/17</td>
<td>95</td>
<td>2</td>
<td>0</td>
<td>-</td>
<td>1.030</td>
<td>7.0</td>
<td>75</td>
</tr>
</tbody>
</table>

Figure 31: Prototype After Salt Spray Test by Swagelok
7 **DISCUSSION**

In this project, our team created a Gantt chart (See. Appendix 10.1) in order to keep our tasks on time and we had meetings with Joe our technical sponsor biweekly to give updates on our progress. Moreover, our first task in our weekly meetings were to brainstorm ideas using the existing hand tube bender methods and some designs that could be alternative designs. Then we continued our steps by designing them in SOLIDWORKS. We also researched the cost for each material that can be used in our hand tube bender designs and calculated the force that can be applied for each design in order to create our weighted design matrix. As a result, from the four designs we had, we were able to narrow it into one single design, the MS-HTB modified hand tube bender otherwise named (MS-HTB-IPT-4 and MS-HTB-IPT-6 for 1/4” and 3/8” benders respectively). In the second half of our project, we continue our design analysis by using finite element analysis software to verify our material selections for our bender by focusing on the yield strength of each component and material. The challenge in manufacturing was maintaining our allotted time per the gantt chart that was developed early in the project but despite these challenges prototypes were made. We tested our prototypes (both ¼” and 3/8” benders) to calculate the ovality and measure the spring back of the tubing selected for testing. Additionally, a corrosion test was performed to validate our design met the oxidation requirements of the project. After analyzing our data there are a few design changes are needed. Firstly, the 3/8” benders shoulder screw, that connected the link and roller housing, yielded. Our suggestions would be to counter bore the link and select a longer shoulder screw. This will allow this hardware component to take more shear force while bending and prevent yielding from occurring. Secondly, during testing it was found that some of the medium pressure tubing had a larger spring back rate than the high pressure tubing that the design was initially based on. Thus, the exit angle of the tube groove will need to be increased to allow a full 180° bend. This increase in tube groove exit angle will require the feature that is designed to be held in a bench vice to be pushed out slightly from the main shoulder screw bolt in the center of the bender die. Without this move the link will interfere with this feature of the bender die when it is past 180° and will not allow for full range of motion, preventing certain types of tubing from obtaining an actual bend angle of 180°.

8 **CONCLUSION**

In the first half of the project, we evaluated the current Swagelok high pressure hand tube bender to obtain baseline data that would be required for our design. Then we started to brainstorm concepts that could potentially meet all the criteria and requirements of the project imposed by Swagelok. Each concept was further analyzed to determine the potential advantages and disadvantages and compared to each other where a selection process, learned from our Concepts of Design class, was utilized to select the best concept. For the most part we have stayed on track with our intended target dates for different tasks throughout the project. Completing tasks on time has been helpful in setting ourselves up for success for the second half of the project.
In the second half of the project, we continued our design iterations and analysis of the tube bender design that was selected. This consisted of using Finite Elements Analysis to determine if our design and material selections were sufficient to meet the forces that would be translated to the different components of the bender assembly. We then created our technical part drawings to send out to the various manufacturers so that a functional prototype could be created. We tested our prototypes by bending a variety of different types of tubing, ranging from standard to high pressure. In addition we performed an ultimate strength test on each size bender and performed a salt spray test. Initially our aim was to have two design iterations which would include two prototyping iterations. However, due to time limitation, only one design iteration was able to be completed. Despite this the results of the prototype benders show they meet all the requirements of the project. The project has been a great educational experience for us and helped improve our abilities and knowledge as young engineers. Moving forward to our future careers, we will be able to build upon this senior design project experience and to help our employers and society overcome other design and engineering problems.
# References


### 10 Appendices

#### 10.1 Gantt Chart

**Table 13: Progress and Timeline**

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Start Date</th>
<th>End Date</th>
<th>Duration (days)</th>
<th>Percent Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second design iteration</td>
<td>21-Nov-2016</td>
<td>28-Nov-2016</td>
<td>7</td>
<td>100%</td>
</tr>
<tr>
<td>Design iterations continued (if necessary)</td>
<td>28-Nov-2016</td>
<td>9-Jan-2017</td>
<td>42</td>
<td>100%</td>
</tr>
<tr>
<td>3D print current design iteration</td>
<td>28-Nov-2016</td>
<td>12-Dec-2016</td>
<td>14</td>
<td>100%</td>
</tr>
<tr>
<td>Submit midterm paper to Swagelok for approval</td>
<td>28-Nov-2016</td>
<td>4-Dec-2016</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>Submit midterm paper to UA</td>
<td>12-Dec-2016</td>
<td>17-Dec-2016</td>
<td>5</td>
<td>100%</td>
</tr>
<tr>
<td>Develop test plan</td>
<td>9-Jan-2017</td>
<td>13-Feb-2017</td>
<td>35</td>
<td>100%</td>
</tr>
<tr>
<td>First prototype manufacturing</td>
<td>1-Feb-2017</td>
<td>1-Apr-2017</td>
<td>59</td>
<td>100%</td>
</tr>
<tr>
<td>Test prototype design iteration 1</td>
<td>1-Apr-2017</td>
<td>16-Apr-2017</td>
<td>15</td>
<td>100%</td>
</tr>
<tr>
<td>Submit final report to Swagelok for approval</td>
<td>10-Apr-2017</td>
<td>21-Apr-2017</td>
<td>11</td>
<td>100%</td>
</tr>
<tr>
<td>Submit final report to UA</td>
<td>8-May-2017</td>
<td>11-May-2017</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Final Presentation</td>
<td>28-Apr-2017</td>
<td>28-Apr-2017</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
10.2 Finite Elements Analysis

Figure 32: FEA Analysis in Bender Die 0.25
Figure 33: FEA Analysis in the handle 0.25
Figure 34: FEA Analysis in the latch 0.25
Figure 35: FEA Analysis in Link 0.25
Figure 36: FEA Analysis in Roller 0.25
Figure 37: FEA Analysis in Roller Housing 0.25
Figure 38: FEA Analysis in Bender Die 0.375
Figure 39: FEA Analysis in Handle 0.375
Figure 40: FEA Analysis in Latch 0.375
Figure 41: FEA Analysis in Link 0.375
Figure 42: FEA Analysis in Roller 0.375
Figure 43: FEA Analysis in Roller Housing 0.375
% Current Swagelok High Pressure Tube Bender
% Input force versus bend angle (theta)
% 0.25" tubing

clear all, close all, clc
M_o = 720; % Moment (lbs-in)

% Relevant distances (inches)
d1 = 1.06;
d2 = 1.75;
d3 = [5 8 11 14.03]; % handle length = 12.45"; d3=14.03" if force applied at end of handle
d4 = 1.75;
theta = -90:1:90;

F_input1 = M_o./(d1.*cosd(theta)+d4.*((cosd(theta)).^2)+d3(1).*((cosd(theta)).^2)+d2.*((sind(theta)).^2)+d3(1).*((sind(theta)).^2));
figure(1);
theta_2 = 0:1:180; % corrected bend angle
F_input1 = fliplr(F_input1);
plot(theta_2,F_input1)
hold on

F_input2 = M_o./(d1.*cosd(theta)+d4.*((cosd(theta)).^2)+d3(2).*((cosd(theta)).^2)+d2.*((sind(theta)).^2)+d3(2).*((sind(theta)).^2));
F_input2 = fliplr(F_input2);
plot(theta_2,F_input2)
hold on

F_input3 = M_o./(d1.*cosd(theta)+d4.*((cosd(theta)).^2)+d3(3).*((cosd(theta)).^2)+d2.*((sind(theta)).^2)+d3(3).*((sind(theta)).^2));
F_input3 = fliplr(F_input3);
plot(theta_2,F_input3)
hold on

F_input4 = M_o./(d1.*cosd(theta)+d4.*((cosd(theta)).^2)+d3(4).*((cosd(theta)).^2)+d2.*((sind(theta)).^2)+d3(4).*((sind(theta)).^2));
F_input4 = fliplr(F_input4);
plot(theta_2,F_input4)

grid on; grid minor;
xlabel('Bend Angle (degrees)');
ylabel('Input Force (lbs_f)');
title('Current Swagelok Hand Tube Bender Input Force (1/4" tubing)');
legend('Handle=5''','Handle=8''','Handle=11''','Handle=14.03''');
Current Swagelok Hand Tube Bender Input Force (1/4" tubing)

0.25" tubing

\[ \text{d5} = 1.5; \]
\[ \text{d6} = 2.61; \]
\[ \text{d7} = 1; \]
\[ \text{d8} = 0.5; \]

```matlab
figure(2)
R1 = (F_input1.*(d3(1)+d6))/d8;
plot(theta_2,R1)
hold on
R2 = (F_input2.*(d3(2)+d6))/d8;
plot(theta_2,R2)
hold on
R3 = (F_input3.*(d3(3)+d6))/d8;
plot(theta_2,R3)
hold on
R4 = (F_input4.*(d3(4)+d6))/d8;
plot(theta_2,R4)
hold on
grid on; grid minor;
```
xlabel('Bend Angle (degrees)');
ylabel('Caster Die Force (lbs_f)');
title('Current Swagelok Hand Tube Bender Caster Die Force (1/4'' tubing)');
legend('Handle=5''','Handle=8''','Handle=11''','Handle=14.03''');

% Input force versus bend angle (theta) 0.375'' tubing

M_o = 1509; % Moment (lbs-in)

% Relevant distances (inches)
d1 = 1.06;
d2 = 1.75;
d3 = [5 8 11 14.03]; % handle length = 12.45''; d3=14.03'' if force applied at end of handle
d4 = 1.75;

theta = -90:1:90;
F_input1 = M_o./(d1.*cosd(theta)+d4.*((cosd(theta)).^2)+d3(1).*((cosd(theta)).^2)+d2.*((sind(theta)).^2)+d3(1).*((sind(theta)).^2));
figure(3);
theta_2 = 0:1:180; % Corrected bend angle
F_input1 = fliplr(F_input1);
plot(theta_2,F_input1)
hold on

F_input2 = M_o./(d1.*cosd(theta)+d4.*((cosd(theta)).^2)+d3(2).*((cosd(theta)).^2)+d2.*((sind(theta)).^2)+d3(2).*((sind(theta)).^2));
figure(3); hold on
plot(theta_2,F_input2)
\[
sind(\theta)^2 + d3(2)\times(sind(\theta)^2)\]

\[
F_{\text{input}2} = \text{fliplr}(F_{\text{input}2});
\]

\[
\text{plot}(\theta_2,F_{\text{input}2})
\]

\[
\text{hold on}
\]

\[
F_{\text{input}3} = \frac{M_o}{d1\times\cosd(\theta) + d4\times(\cosd(\theta)^2) + d3(3)\times(\cosd(\theta)^2) + d2\times(sind(\theta)^2) + d3(3)\times(sind(\theta)^2)};
\]

\[
F_{\text{input}3} = \text{fliplr}(F_{\text{input}3});
\]

\[
\text{plot}(\theta_2,F_{\text{input}3})
\]

\[
\text{hold on}
\]

\[
F_{\text{input}4} = \frac{M_o}{d1\times\cosd(\theta) + d4\times(\cosd(\theta)^2) + d3(4)\times(\cosd(\theta)^2) + d2\times(sind(\theta)^2) + d3(4)\times(sind(\theta)^2)};
\]

\[
F_{\text{input}4} = \text{fliplr}(F_{\text{input}4});
\]

\[
\text{plot}(\theta_2,F_{\text{input}4})
\]

\[
\text{grid on; grid minor;}
\]

\[
\text{xlabel('Bend Angle (degrees)')};
\]

\[
\text{ylabel('Input Force (lbs_f)')};
\]

\[
\text{title('Current Swagelok Hand Tube Bender Input Force (3/8" tubing)')};
\]

\[
\text{legend('Handle=5''', 'Handle=8''', 'Handle=11''', 'Handle=14.03''')};
\]
\begin{verbatim}
d5 = 1.5;
d6 = 2.61;
d7 = 1;
d8 = 0.5;

figure(4)
R1 = (F_input1.*(d3(1)+d6))/d8;
plot(theta_2,R1)
hold on

R2 = (F_input2.*(d3(2)+d6))/d8;
plot(theta_2,R2)
hold on

R3 = (F_input3.*(d3(3)+d6))/d8;
plot(theta_2,R3)
hold on

R4 = (F_input4.*(d3(4)+d6))/d8;
plot(theta_2,R4)
hold on

grid on; grid minor;
xlabel('Bend Angle (degrees)');
ylabel('Caster Die Force (lbs_f)');
title('Current Swagelok Hand Tube Bender Caster Die Force (3/8" tubing)');
legend('Handle=5"','Handle=8"','Handle=11"','Handle=14.03"');
\end{verbatim}
% Input force versus bend angle (theta) for MS-HTB-IPT-4

clear all, close all, clc
M_o = [563 416.2]; %Moment (lbs-in)

% Relevant distances (inches)
d1 = [1.0625 0.91];
d2 = [1.75 1.875];
d3 = [14.03 13.672 14.444]; %handle length = 14.03" (Current Bender); 16" (Modified MS-HTB)
d4 = [1.75 1.875];
d5 = 1.18;

% Swagelok Hand Tube Bender force input analysis
theta = -90:1:90;
F_input1 = M_o(1)./(d1(1).*cosd(theta)+d4(1).*((cosd(theta)).^2)+d3(1).*((cosd(theta)).^2)+d2(1).*((sind(theta)).^2)+d3(1).*((sind(theta)).^2));
figure(1);
theta_2 = 0:1:180; %corrected bend angle
F_input1 = fliplr(F_input1);
plot(theta_2,F_input1,'k')
hold on

% MS-HTB-IPT force input analysis (handle at 90\degree to stationary handle at 0\degree bend)
beta = 10; %degrees
F_input2 = M_o(2)./(d1(2).*sind(theta+beta)+d4(2).*((cosd(theta).*sind(theta+beta))... +d3(2).*((sind(theta)+beta).*sind(theta+beta))+d2(2).*((sind(theta).*cosd(theta+beta)).^2)... +d5.*(sind(theta).*cosd(theta+beta))+d3(2).*((sind(theta+beta).*sind(theta+beta))^2));
theta_2 = 0:1:180; %corrected bend angle
F_input2 = fliplr(F_input2);
plot(theta_2,F_input2,'b')
hold on

% MS-HTB-IPT force input analysis (handle at 180\degree to stationary handle at 0\degree bend)
F_input3 = M_o(2)./(d1(2).*cosd(theta)+d4(2).*((cosd(theta)).^2)+d3(3).*((cosd(theta)).^2)+d2(2).*((sind(theta)).^2)+d3(3).*((sind(theta)).^2));
F_input3 = fliplr(F_input3);
plot(theta_2,F_input3,'r')
hold on

grid on; grid minor;
xlabel('Bend Angle (degrees)');
ylabel('Input Force (lbs_f)');
title('Tube Bender Force Input Comparison');
% Input force versus bend angle (theta) for MS-HTB-IPT-6

M_o = [1509 1321.6]; % Moment (lbs-in)

% Relevant distances (inches)
d1 = [1.0625 1.37];
d2 = [1.75 1.968];
d3 = [14.03 20.01 20.89]; % handle length = 14.03" (Current Bender); 16" (Modified MS-HTB)
d4 = [1.75 1.968];
d5 = 1.44;

% Swagelok Hand Tube Bender force input analysis
theta = -90:1:90;
F_input1 = M_o(1)./(d1(1).*cosd(theta)+d4(1).*((cosd(theta)).^2)+d3(1).*((cosd(theta)).^2)+d2(1).*((sind(theta)).^2)+d3(1).*((sind(theta)).^2));
figure(1);
theta_2 = 0:1:180; % corrected bend angle
F_input1 = fliplr(F_input1);
plot(theta_2,F_input1,’--k’)
hold on

% MS-HTB-IPT force input analysis (handle at 90° to stationary handle at 0° bend)
beta = 10; % degrees
F_input2 = M_o(2)./(d1(2).*sind(theta+beta)+d4(2).*((cosd(theta)).*sind(theta+beta)).*
+ d3(2).*((sind(theta)+beta).*sind(theta+beta))+d2(2).*((sind(theta)).*cosd(theta+beta)).
..
% MS-HTB-IPT force input analysis (handle at 180° to stationary handle at 0° bend)
F_input3 = M_o(2)./(d1(2).*cosd(theta)+d4(2).*((cosd(theta)).^2)+d3(3).*... 
 (((cosd(theta)).^2)+d2(2).*((sind(theta)).^2)+d3(3).*((sind(theta)).^2));
F_input3 = fliplr(F_input3);
plot(theta_2,F_input3,'--r')

% grid on; grid minor;
% xlabel('Bend Angle (degrees)');
% ylabel('Input Force (lbs_f)');
% title('Tube Bender Force Input Comparison');
legend('Current Bender (0.25")','MS-HTB-IPT-4 (90°) ','MS-HTB-IPT-4 (180°) ','Current Bender (0.375")','MS-HTB-IPT-6 (90°) ', 'MS-HTB-IPT-6 (180°) ');