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Wear-Resistant Extrusion Auger for the Production of Charcoal Briquettes from Agricultural Waste

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UNDER MY SUPERVISION BY

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WEAR-RESISTANT EXTRUSION AUGER FOR THE PRODUCTION OF CHARCOAL BRIQUETTES FROM AGRICULTURAL WASTE

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WEAR-RESISTANT EXTRUSION AUGER FOR THE PRODUCTION OF CHARCOAL BRIQUETTES FROM AGRICULTURAL WASTE

By

Maureen O'Neill and Aaron Wagner

SENIOR DESIGN PROJECT REPORT

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Abstract

Ugandan social enterprise AEST makes and sells agricultural waste charcoal briquettes. The extrusion auger used wore down quickly, hampering production. The team worked to find a better material or heat-treatment process to improve the auger's lifetime. The team built a custom pin-on-disk testing apparatus and used it along with optical microscopy to analyze the wear mechanism. The team then heat-treated and tested additional samples to find the best treatment. The team suggested improving AEST’s current case hardening process by increasing the case depth to 0.04 in (0.1016 cm) and using oil quenching.

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Thank you to Don MacCubbin and Calvin Sellers from the SCU Machine Shop for invaluable advice and help with fabrication of our apparatus.

Thank you to Chip Koehler and BJ Hamel, our industry advisors, for help with bringing our apparatus to life.

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1 Introduction

1.1 Background and Motivation

The social enterprise Appropriate Energy Saving Technologies Limited uses recycled agricultural waste to make charcoal briquettes to sell. They are a woman-registered organization that operates in the Teso Region of Uganda. They aim to provide energy solutions for low-income households in the area, and in addition to producing charcoal briquettes; they also make and sell cook stoves [1].

AEST makes their charcoal briquettes through a process called extrusion. Extrusion is the process of pushing a moldable material through a hole at the end of a large drum to create a long, even bar of the material. The auger is the large screw that rotates in the middle of the drum to move the material through. As the part that does the most work and experiences the most force, the auger is the component most vulnerable to wear.

AEST's main problem was that the auger shaft of their charcoal extruder wore out quickly. A new material or hardening method needed to be found to increase the life of the extrusion auger. AEST currently case hardens their augers using pack carburization to a case depth of 0.02 in (0.0508 cm) and uses water as a quenchant after case hardening. This method has shown promise, but the reported improvements have not been quantified. Previous projects have focused on the surface hardness achieved by different quenchants but not whether this increase in surface hardness was sufficient to resist wear [2]. This project aimed to determine the primary wear mechanism acting on the metal auger, and quantify the effects of case hardening on wear resistance.

Figure 1 - A new AEST auger (top) and a twice-repaired auger (bottom), reproduced with permission [2].

1.2 Project Goals

The overall goal was to find a new material or heat treatment process for the auger to make it last longer before wearing down. The first and most time-consuming goal was creating a pin-on-disk machine to test and determine the wear mechanisms that degrade the auger so quickly. Once the reason for the wear was known, the next goal was to design, apply and test combinations of material and heat treatment to resist the wear, in an iterative process. Choosing the best combination after the tests fulfilled the overall goal. The team aimed to find a new material or hardening process to allow AEST to continue using the same extruder machine. Ideally, a new material would not be needed and they could simply modify their existing augers. Improving the auger will most likely increase cost, and this increase in cost must be justified by the increase in lifespan.

1.3 Literature Review

1.3.1 Surface Hardening

Surface or case hardening is used to improve the wear resistance of steel parts without affecting the interior [3]. The diffusion method of surface hardening involves chemically modifying the surface of the part by soaking carbon particles into the surface of steel. Common diffusion methods include carburizing, nitriding, carbonitriding, and boriding [3].

Carburizing is a kind of surface hardening that involves increasing the carbon content of steels at the surface. Increasing the carbon content of steel will increase hardness but also brittleness. For this reason case hardening is used as it does not affect the interior of the part. Pack carburizing involves submerging a steel sample in a crucible full of high-carbon media such as graphite or charcoal, and heating the specimen in a furnace. Pack carburizing is losing favor in industry due to lack of precise case depth control and mess involved in packing process [4]. However, it remains the lowest-cost and most accessible method of case hardening. Pack carburizing is performed in a furnace at temperatures of 1500-1750 ˚F (815-954 ˚C), and the rate of case hardening increases with temperature. However, using a lower temperature will yield a smaller variation in case depth, which is ideal for low depth operations. Carburizing containers are commonly made from carbon steel or ceramic, and may have an alloy coating. Although this project used alumina ceramic crucibles that needed no preparation, with an alloy-coated container it is important to "precarburize" the container before placing it in service to ensure the container itself will not be carburized along with the work load. An extra process control specimen can be included in the container with the work piece in order to test case-depth and perform other tests that would harm the piece [4].

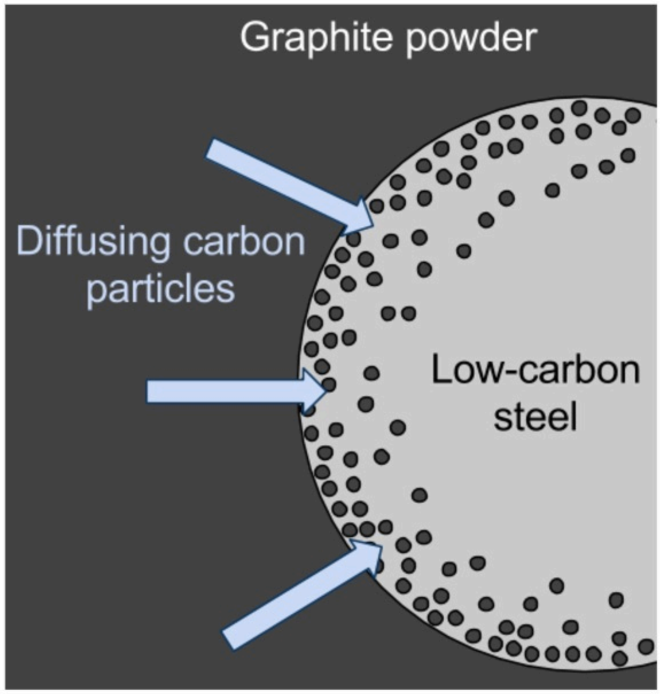

Figure 2 – Diagram of Carburizing Process.

The depth of the case hardened region is dependent on the diffusivity constant, the temperature, and the process time. The general formula for carbon concentration at a certain case depth can give the most detailed information about a theoretical case hardening procedure, but also involves the complicated "error function" erf:

$$\boldsymbol{C = C_s - (C_s - C_0) \cdot erf\left(\frac{x}{2\sqrt{Dt}}\right)} \qquad \textbf{(Eq. 1)}$$

C is the carbon concentration at depth x from the material surface, C_s and C_0 are respectively the concentrations at the surface (usually 100%) and the center (the untreated metal's concentration), D is the diffusion rate calculated by its own formula, and t is the amount of time spent diffusing at that rate.

A recommended concentration C to examine is halfway between C_s and C_0 such that the erf term is 0.5. Conveniently, this occurs when everything inside erf is also 0.5, so at this particular concentration the case depth equation becomes:

$$\boldsymbol{x = \sqrt{Dt}} \qquad \textbf{(Eq. 2)}$$

where D is evaluated by:

$$\boldsymbol{D = D_0 \cdot exp(\frac{-Q}{RT})} \qquad \textbf{(Eq. 3)}$$

D_0 is a diffusivity constant that depends on the materials (0.23 cm^2/s for carbon into steel), Q is an energy constant (32,900 cal/mol for these conditions), R is the ideal gas constant, and T is the temperature in degrees Kelvin. The team used this concentration to evaluate the expected case depths from different heat treatment times and temperatures.

1.3.2 Quenching

After hardening, most steel pieces are quenched to promote the development of martensite. Different quenching media offer different rates of heat extraction. Direct quenching is the most commonly used method and involves quenching directly from the austenitizing temperature. This is the method currently used by AEST. Other methods of quenching are time quenching, where multiple quenchants are used in succession to control heat extraction; selective quenching, where only certain areas of the part are quenched; spray quenching, used on areas where a higher cooling rate is desired; fog quenching, used where a lower cooling rate is desired, and interrupted quenching [5].

There are three primary stages of quenching. During A-stage, a vapor blanket forms around the part and insulates it, causing slower cooling. During B-stage the vapor blanket collapses and higher heat extraction rates are achieved. The quenchant is vaporized when it touches the surface of the part, referred to as nucleate boiling. At C-stage the temperature at the part surface has dropped below the boiling temperature of the quenchant. Cooling occurs through conduction and convection during C-stage [5]. These stages can be seen in Figure 3.

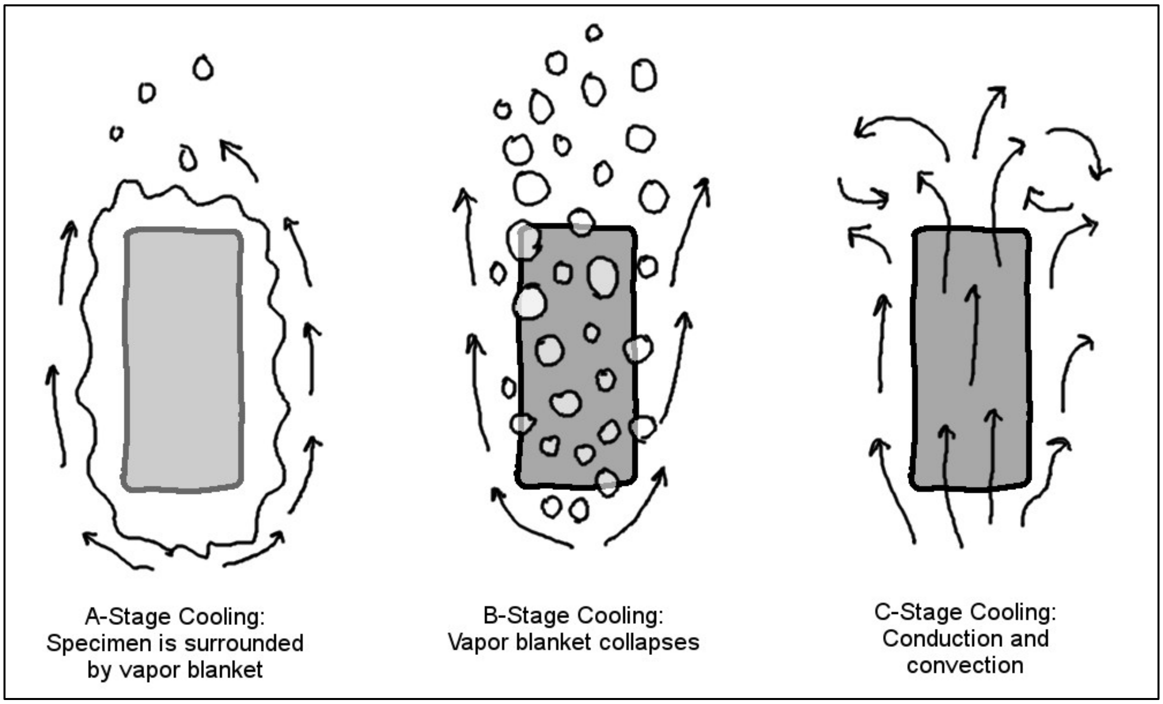

Figure 3 – Diagram showing the three stages of quenchant cooling.

1.3.3 Wear Mechanisms

Wear is mechanically induced surface damage that involves the removal of material from a surface over time. Usually there is more than one wear mechanism acting on a machine part, and corrosion or other effects can also exacerbate mechanical wear. Sliding wear is the tangential motion between two surfaces in contact, and two-body abrasive wear is wear from hard particles moving over a surface. Other common wear mechanisms include fretting wear, fatigue wear, impact wear, and polishing wear. Chipping and scratching are not technically wear methods because they can occur after one contact but they still cause surface damage and are commonly included in discussion with other true wear methods [6].

1.3.4 Pin-on-Disk Testing

Pin-on-disk testing is used to understand the sliding wear between two different materials. One specimen is a pin with a spherical tip and the other specimen is a flat disk. Either the pin or disk rotates creating a circular sliding path. Various material combinations are tested and the results are compared. For a pin-on-disk apparatus, the results can be considered more accurate the closer the testing environment mimics the working environment, however it is often impractical to fully recreate the working environment. For this reason, pin-on-disk testing can only predict the relative ranking of different material combinations, and should be combined with other testing methods to produce a clear picture of the wear mechanism. Tribology alone cannot accurately predict the lifetime of a part, but can predict the relative lifetimes of different part materials [7].

Although there are commercially available pin-on-disk testing machines, most pin-on-disk testing apparatuses have been custom produced for a specific experiment in order to better model the wear environment of a specific system. As such, it is difficult to compare the results from one study to another.

While adhering to the established standard, ASTM G99, can help, it is necessary to fully understand the applied conditions of each result set in order to compare them [7].

1.3.5 Sample Preparation

Before and after mounting, organic solvents are recommended for removing oils, coolants, and other residue that may interfere with the mounting process or examination. Once clean, the sample can be mounted in plastic to facilitate examination of fragile or oddly shaped samples, as well as any sample edges. These plastics, such as epoxy, consist of a resin and a hardener. The two components are mixed to begin the chemical reaction and then immediately poured in a cup around the sample. Depending on the plastic used, the mixed components will solidify in a matter of minutes or hours, often generating heat. This surrounds the sample in solid plastic, which must be ground down to ensure the sample surface is consistently exposed. Grinding begins with rough "planar" grinding to remove obstructions from the mount and level the sample surface. Fine grinding then removes damage caused by the rough grinding. Once ground thoroughly and then cleaned with a corrosion-inhibiting water/soap solution, the sample is fit for examination [8].

1.3.6 Microhardness Testing

Microindentation Hardness Testing, more commonly known as microhardness testing, tests a material's hardness by making a very small indentation in it under a known force. Specifically, a diamond tool indents with the surface at a force between 1 and 1000 gram-force (about 0.01 to 10 Newtons) [9]. Depending on the test method and shape of tool used, either the diagonal dimensions of the indentation or its depth determine the material's hardness on a particular scale. The Vickers and Knoop scales are based on dimensions while the Rockwell scale is based on depth [10].

1.3.6.1 Vickers Hardness

In a Vickers hardness test, a pyramidal diamond tool smoothly presses into a material with a specified force for a known dwell time, usually between 10 and 15 seconds. This creates a square indentation whose diagonals are then measured. The average of the two measurements (in micrometers) is used as d in the hardness equation:

$$\textbf{Vickers Hardness} = \boldsymbol{HV} = \frac{\boldsymbol{2000P \cdot sin(\alpha/2)}}{\boldsymbol{d^2}} = \frac{\boldsymbol{1854.4P}}{\boldsymbol{d^2}} \qquad \textbf{(Eq. 4)}$$

where P is the applied load in gram-force and α is 136° in a standard Vickers tool, which has been used to form the second part of the equation. This scale was designed to very closely match the results of a Brinell test while being more feasible to perform on hard steels. Unlike the Rockwell test elaborated in the next section, the Vickers test advantageously has only one scale for all materials [9].

1.3.6.2 Rockwell Hardness

The previous team from MIT used the Rockwell scale for their hardness tests. A Rockwell hardness testing machine presses an indenter, either spheroconical diamond or a tungsten carbide ball, into the material being tested. Once the indenter is in contact, a preliminary test force F_0 is applied, and the indentation depth is measured after the force is held for a known dwell time. An additional test force is then added at a specified rate to reach the total test force F, also held for a known dwell time. No measurements are made at this intermediate step. After the dwell time, the additional force is released and the indenter presses with the preliminary force F_0 again for a final dwell time. The increased indentation depth is then measured. The difference between these depths is calculated as h (in millimeters) for the equation:

$$\textbf{Rockwell Hardness} = HR = 100 - \frac{h}{0.002} \qquad \textbf{(Eq. 5)}$$

Multiple scales exist depending on the indenter material, total test force, and type of material being measured. For instance, a Rockwell hardness measured using a diamond indenter and 150 kgf total test force is on the C scale and denoted HRC [11].

2 Systems-Level Chapter

2.1 Customer needs, system level requirements

The auger used in AEST's charcoal briquette extruder was custom designed by a local manufacturer, in conjunction with researchers from the MIT D-Labs. AEST expressed strong preference for locally manufactured extrusion augers, but they were willing to import as a last resort as their desire to increase production took precedence over the desire to avoid importing.

Table 1 outlines the main customer needs as discovered through multiple interviews with the CEO of AEST and academic advisors. Summaries of these interviews can be found in Appendix E. The highest priority needs were increasing the auger lifetime, maintaining or improving the cost to lifetime ratio, and designing a process to modify the current augers rather than purchasing new ones.

Table 1 - Customer needs, categorized and prioritized 1-5 with 1 most important

Category	Need	Priority
Performance	**Increase in auger lifetime**	**1**
	Stable improvement - not undone over time	3
	Increase in extruder production speed	5
Local Feasibility	**Reuse/modify currently used augers**	**1**
	Improvement process doable in Uganda	2
	Added materials available in Uganda	2
Economy	**Equivalent or better cost/lifetime ratio**	**1**
	Minimized extraneous costs (e.g. shipping)	4

2.2 System sketch

Much of the rest of this chapter will focus on the pin-on-disk machine the team created as part of improving the auger. Figure 4 shows the process of using a pin-on-disk apparatus to test how much a material wears down in a set length of time.

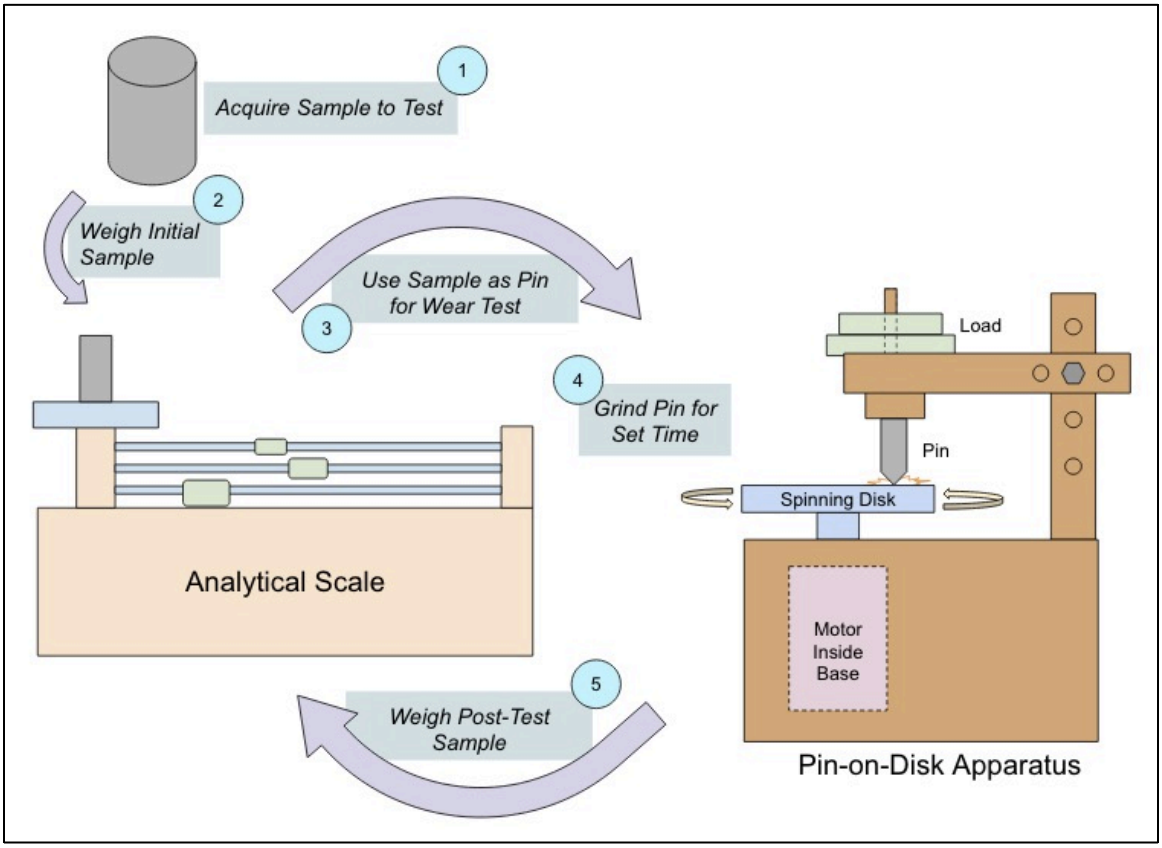

Figure 4 - Process of using pin-on-disk machine to test wear on sample.

For the pin-on-disk machine in particular, user involvement is limited to the setup of the pin, disk, and load, as well as turning the motor on and off after a known amount of time. Otherwise the machine runs automatically once activated. During testing, the apparatus is housed in the fume hood, providing another layer of protection between the user and the moving parts.

2.3 Functional Analysis

Table 2, Table 3, and Table 4 outline the main functions and subfunctions for the pin-on-disk apparatus, the container that will house the apparatus during testing and storage, and the extrusion auger. Table 5 and Table 6 outline the overall inputs and outputs associated with these systems.

Table 2 - Pin-on-Disk Functional Decomposition

Main Function	Sub-Functions
Support pin above disk	Allow variable height Allow horizontal offset
Contain ground charcoal	Facilitate greater measure of similarity between real-world conditions in the auger and testing conditions
Press pin to charcoal and disk	Allow variable load Allow force to be easily measured
Apply grinding motion	Rotate disk Support disk Allow variable speed
House electronics	Protect electronics from charcoal dust particles Protect electronics from water Allow access to electronics when needed
Provide damping	Minimize vibration
Support vertical arm	Multiple pin joint holes to allow for flexibility in motor and pin size

Table 3 - Apparatus Housing Functional Decomposition

Main Function	Sub-Functions
Protect device	Protect apparatus from elements Protect apparatus from other fume hood users
Protect user	Protect user from flying debris Contain charcoal dust Inhibit fire Prevent pinch-points Prevent access to spinning disk during operation Protect user from electrical shocks and hazard

Table 4 - Auger Functional Decomposition

Main Function	Sub-Functions
Move moldable material	Provide sufficient force to push material through extruder die
Resist Wear	Resist corrosion Resist abrasion Resist adhesion
Resist deformation	--
Allow installation/removal from extruder	--

Table 5 - Input Functional Decomposition

System	Inputs	Sub-Inputs
Pin-on-Disk	Material	Insert pin Insert disk Adjust height (Optional) Add load Add charcoal
	Information	(Optional) Time to run Disk RPM Start command
	Energy	Electricity to motor/optional electronics
Auger	Material	Hardening treatment Moldable substance for extrusion
	Information	Start/stop command
	Energy	Rotational motion

Table 6 - Output Functional Decomposition

System	Outputs	Sub-Outputs
Pin-on-Disk	Material	Worn pin Worn disk Moved/scattered charcoal
	Information	RPM output displayed on motor driver
	Energy	Friction heat Loud sound
Auger	Material	Extruded material Wear on auger Deformed auger flights
	Information	N/A, auger has no electronic parts
	Energy	Friction heat (large) Sound

2.4 Benchmarking Results

There are several varieties of pin-on-disk tribometers for sale that loosely inspired the design of this project's pin-on-disk machine. These full tribometers include more features than necessary for the project, such as software and electronic equipment for collecting and displaying real-time data during tests. Most relevant is that these tribometers are compatible with ASTM G99, the same standard that the custom pin-on-disk tester was designed to follow. Figures 2 through 4 on the next page show the most relevant pin-on-disk devices on the market. Table 7 outlines several specifications for each device.

Table 7 - Comparison of three Pin-on-Disk Testers on the market

Name	Manufacturer	Friction Force	Maximum Normal Load	Max Disk Dimensions	Rotation Speed
K93500 Pin-On-Disc Tester	Koehler Instruments	0-200 N	200 N	160 mm diameter	100-2000 rpm
Pin-on-Disk Tribometer	Anton Paar	Up to 10 N	10 N	60 mm diameter	1-500 rpm
TE-165- SPOD	Magnum Engineering	0-200 N	200 N	165 mm	100-2000 rpm

These commercial pin-on-disk devices are part of larger, electronically aided systems that measure other parameters this project will not need, such as coefficient of friction. Thus the high expense was not worthwhile for these extra features. Most importantly, the available devices are generally enclosed and precisely constructed, which would have made it impractical to add charcoal to the disk and simulate the necessary wear conditions. If the charcoal could be applied at all to one of the commercial products, it would likely damage the device and render the results unreliable. Building a pin-on-disk testing apparatus allowed for customization and a lower cost overall.

In short, purchasable pin-on-disk machines would not meet the very important criterion of charcoal applicability and might exceed the criteria of weight and portable size. It was important for the pin-on-disk testing apparatus to be light enough to be carried by one person, preferably less than 15 pounds. Although the charcoal dust turned out to be easily contained by a fume hood, we wanted to be able to move the machine regularly if necessary to protect the machines in Dr. Sepehrband's lab space from charcoal dust. While cost was not included as a criterion for deciding between our own custom designs, premade machines also cost too much to fulfill the basic needs of the project.

2.5 System-Level Layout

2.5.1 Auger

Figure 5 shows a simple diagram of where the auger fits into the extruder's other components and what material elements affect the auger's performance.

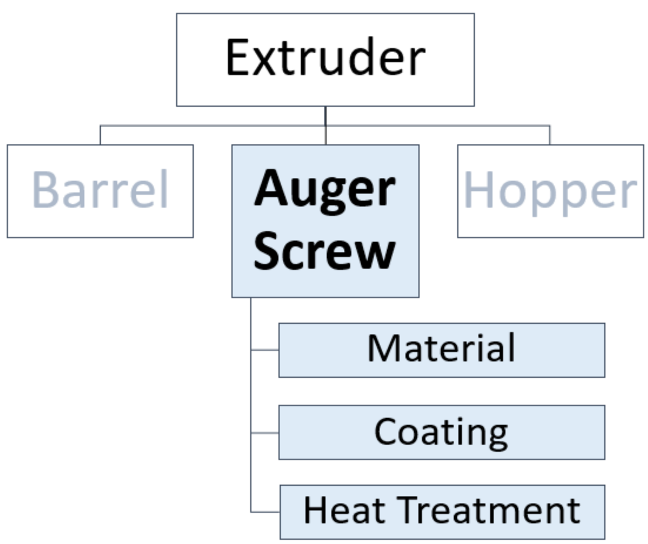

Figure 5 - System sketch of auger and its material components within extruder.

The overall extruder has a few components: the barrel containing the moldable material, the hopper that feeds material into the back of the barrel, and the auger screw that moves material forward through the barrel until it is squeezed out of the extruder in the desired shape. The auger, in turn, has several properties that the project will examine. The main material makes up the bulk of the auger and is usually a form of steel. Heat treatment then shifts the material between hardness and ductility; annealing makes the metal more flexible and soft, while a steel hardening process adds carbon to the outside surface and raises both its strength and brittleness (without affecting the interior). Keeping the interior soft is very important to prevent an auger from breaking during operation. A thin layer of coating may finally be applied to the outside surface, typically a non-reactive and thus corrosion-resistant metal.

Operating an extruder is fairly simple for the user. AEST's extruder is electrically powered and only requires the user to feed material into the hopper once the motor is activated. The organization members in Teso have been using the same extruder for a long time; since this project will most likely modify the same augers they have been using without significantly altering their dimensions, using the improved augers should not be an issue.

2.5.2 Pin-on-Disk Machine

Figure 6 shows the system breakdown for the pin-on-disk machine in several levels. The subsystem chapters expand on the design ideas for the frame, electronics, and charcoal applicator.

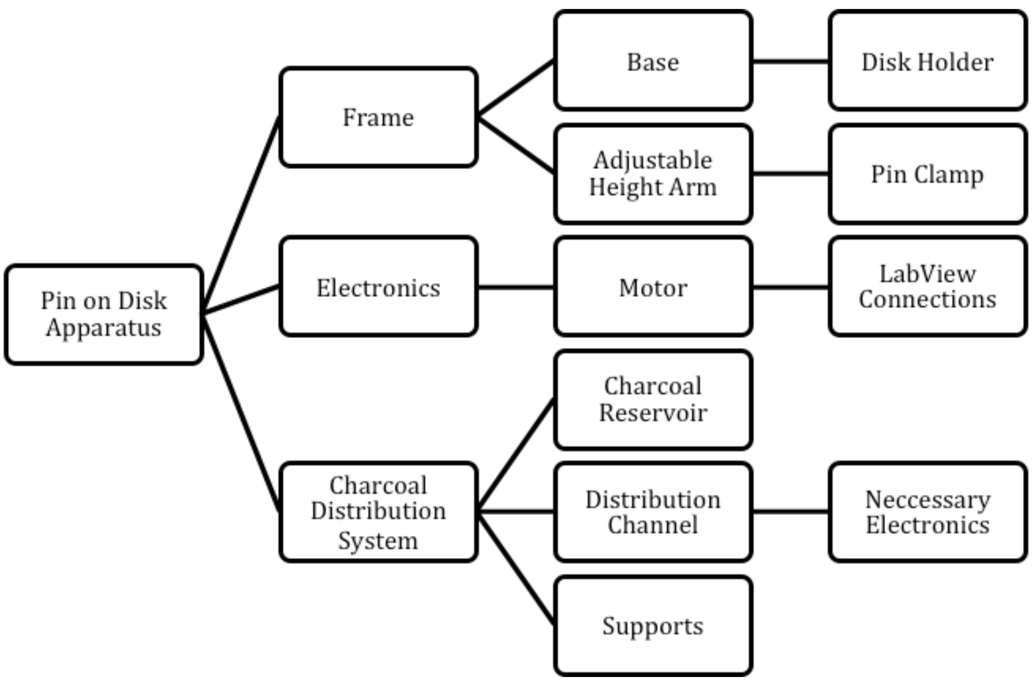

Figure 6 - Systems Level Sketch of Pin-on-Disk Apparatus.

3 Team and project management

3.1 Project challenges and constraints

The main constraint facing our team is that the augers must be designed for a machine that is in Uganda, and will not be able to be tested in the field before the final combination is suggested to AEST. However, as much information has been gathered on this machine as possible, through interviews with AEST and MIT D-Lab employees and previous reports.

Another challenge will be accurately replicating auger conditions during pin-on-disk testing, with the highest level of realism. This has been accomplished by using a cup-shaped disk so that charcoal surrounds the pin at all times. Through interviews with former project members and talking with industry professionals at the Conceptual Design Review, we believe this design will accurately reflect the auger conditions when in operation inside the extruder. Although a part of the auger was received from AEST, it was a slice of the auger flight that had been welded multiple times and could not be used as a reliable test specimen of the base metal. The team also asked for samples of the cassava root charcoal powder made by AEST, but was told it would not be possible to ship to California. This setback was discussed with the project advisor, and it was determined that using ground natural wood charcoal would be an acceptable substitute.

A major challenge was finding a motor for the apparatus. Initially, the team purchased a used motor that came out of a Buehler twin polisher-grinder for $75 off of EBay. Motors of this kind are usually over $500. They hoped to be able to find information on the motor and hook it up to a driver system or variac controller, however the information was considered proprietary by the manufacturer and was not available. Deciding that it was unsafe and unwise to attempt to use this motor in the apparatus, the team purchased a complete DC motor system from Oriental Motors for $450. The drive shaft of the Buehler motor was modified and used in the apparatus. Although the team wanted to be frugal with their motor choice, it would have been a much better course of action to initially buy a complete motor system. The related delays in apparatus assembly were mitigated in part by the adjustability of the horizontal and vertical arms. The arms were designed before the Buehler motor was purchased, and were consciously designed to accommodate apparatuses of different heights and widths.

A limiting factor was the long trial lengths and the time needed to heat treat specimens. Each trial was 5 hours long and heat treatment took up to 7 hours. This limited the number of specimens that could be reasonably tested. Although the results of the experiment are satisfactory and are consistent with the expected trends in wear resistance, the reliability of the results could be improved by running repeat trials.

3.2 Budget

This section gives an overview of the estimated budget and received income in paragraph form Table A 1, Table A 2, and Table A 3, found in Appendix A, outline the budget, income, and complete expenditures in tabular form.

The proposed was that $1500 would go toward the materials needed to build a pin-on-disk testing machine for the first stages of the project. Another $1500 would be needed for consumable supplies during testing. $500 was set aside to pay for a contractor to apply coatings to samples, however this was not accomplished due to time constraints. An ambitious travel budget of $2000 was projected to send both team members to a humanitarian engineering conference to present the results at the end of the project.

The group applied for the Roelandts Grant requesting $5000 (all except transport for one team member) and received $4000. The team also applied for the general senior design grant from the School of Engineering, and received $1000. This was used to cover funds not provided by the Roelandts Grant, as well as allow one student to travel to a conference.

3.3 Timeline

This section is an overview of the project timeline. A more detailed Gantt chart can be found in Appendix A as Table A 4.

Fall quarter was mainly time for gathering information and materials, as well as designing a pin-on-disk testing apparatus. The team made contact with AEST, the MIT D-Labs, the MIT chapter of Engineers Without Borders, as well as a group of MIT students travelling to Uganda in January. Interviews were conducted with Betty Ikalany of AEST, Dan Sweeney and Lindsey Wang of MIT, Dr. Sepehrband, and Dr. Marks to assess customer needs and possible solutions. A sample of the auger was mailed by Betty Ikalany to Santa Clara, but was unable to be used as it was from the far edge of a welded flight instead of a full slice of the auger as the team had hoped. The pin-on-disk testing machine was designed over the course of the quarter, with many different designs considered, including both spinning pin and spinning disk designs. Don MacCubbin, of the SCU Machine Lab, was consulted to assess feasibility. Additionally, the team applied to be paired with an industry mentor through the School of Engineering.

Winter quarter was spent finalizing the design of the pin-on-disk apparatus and then fabricating it. The design was switched from a spinning pin to a spinning disk configuration, to allow for the charcoal cup that was part of the final design. Production of the apparatus was hindered as only one of the student members had machine shop certification. The team fabricated the pin specimens throughout the quarter. Additionally, the team sourced a second hand motor from a Buehler twin polisher-grinder to use as the apparatus motor. However, there were issues with proprietary information from the motor's manufacturer and this option was determined to be unsafe. As this first motor was only $75, there was more than enough money left over to purchase a new complete motor system. The team consulted with their industry advisor Chip Koehler as well as Dr. Sepehrband and purchased a motor from Oriental Motor Systems. The team also did finite element analysis to determine whether the horizontal arm could withstand the forces it would be under during operation.

The apparatus fabrication was completed the first week of spring quarter. An additional structure was fabricated to house the motor driver, which has a heat sink and therefore very specific requirements for operation. The team purchased an analytical scale and then was able to start testing. Several trials were run with pins that would not be in the final data set to ensure satisfactory operation of the apparatus and testing procedure. A run time of 5 hours with a speed of 300 rpm was chosen to balance measurable mass loss, charcoal dust loss, and the ability to run multiple tests in one day. The rest of the quarter was spent fabricating pins, carburizing them in the materials lab, running pin-on-disk testing, and then analysis. Analysis consisted of imaging under a microscope and Vickers hardness testing. After comparing the wear resistance results from different heat treatments, the team performed cost analysis on the different proposed solutions.

3.4 Design process

The process took place in five main steps, as shown in Figure 7. Detailed descriptions of each task follow.

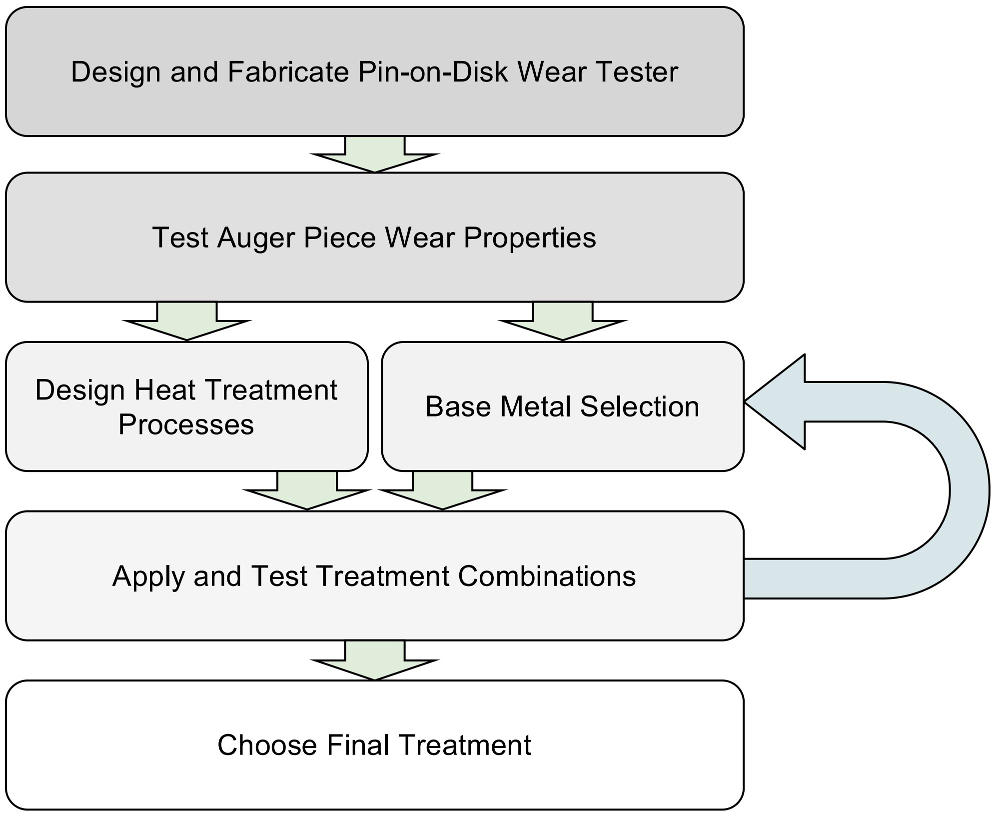

Figure 7 - Visual flow of overall design process.

Task 1: Design and build testing equipment.
The first device needed was a pin-on-disk testing machine to measure how much material the augers lose in a certain length of operating time. A pin-on-disk apparatus consists of a rotating disk and a round-tipped pin, where the pin is pressed down on the spinning disk to grind the two together. The Pin-on-Disk subsystem chapter details the design process for this task.

Task 2: Test material of existing augers to determine wear mechanism.
The degrees of wear on the pin and disk are measured separately by how much mass each has lost after a specific amount of time. Both specimens are weighed before and after the test to measure this. The test is typically repeated with a different force and rotation speed each trial [ASTM Standard G99-05].

In our case the initial pins were small rods of 1018 steel, similar to the mild steel of AEST's augers. After pin-on-disk testing, microscopes were used to examine the worn edges and determine if the material was being solely ground away through erosion, or if an acidic or rusting effect was corroding it at the same time. Light-based microscopes were used in Santa Clara University's materials lab.

Task 3: Design heat treatments.
The information gained from Task 2 guided the design of the heat-treatment procedures applied to more samples of 1018 steel. Heating pins immersed in carbon (specifically graphite powder) hardened the outside of the metal to strengthen it against erosion. While the wear mechanism was found to only noticeably consist of erosion, a coating of non-reactive metal could also have prevented corrosion from reaching the more reactive steel if needed. Multiple time and temperature combinations were tried in order to achieve different case hardening depths, as outlined later in the experimental procedure.

Task 4: Apply and test designed heat treatments and other base metals.
The heat treatments were performed in the tube furnace of the Santa Clara University materials lab. In addition to these hardened samples, a few pins of other base steel compositions (1045, 12L14, and 8620) were tested in the pin-on-disk machine for comparison with the initial pins. To see whether the treatment had increased hardness near the surface as expected, microhardness testing was then performed on smaller cylindrical samples case hardened with the pins. This testing was done in Dr. Sepehrband's research lab. This task was also reiterated with the data gained from the first round of tests. About half of the treatments designed were guided by seeing which heat treatments were feasible with the available equipment and effective during pin-on-disk testing.

Task 5: Analyze test results and make final conclusions.
The tests from Task 4 revealed the reduction of mass loss among heat treated samples and harder base materials in comparison to untreated mild steel. The data was considered alongside economic and feasibility concerns to prepare a set of final recommendations for AEST.

3.5 Risks and mitigations

Table 8 - Risks and safeguards at each project stage.

Project Phase	Risks and Safeguards
Manufacture	Risk: Machining Hazards ● Metal-cutting Machine ● Bending sheet metal ● Drilling holes Safeguards: ● Follow all lab safety procedures ● Lab machines are thoroughly equipped with safety measures Risk: Sharp-edged sheet metal Safeguard: ● File all metal edges to make them safely rounded
Assembly	Risk: Powerful adhesives for mounting pins ● Sticking to fingers, clothes ● Possible fumes Safeguards: ● Wear gloves during adhesive application ● Perform in an open area to ventilate any fumes Risk: Moderately strong magnets for attaching front panel ● Finger pinching ● Slight chance of electronic interference Safeguards: ● Final position of panel leaves space for fingers ● Magnet side against wall so no devices accidentally contact
Testing/Operation Testing/Operation Cont.	Risk: High-speed spinning disk Safeguard: ● Although the spinning disk will be above the top surface of the base, it will be a low as possible so fingers would not be able to fit under/be stuck underneath Risk: Rotating shaft underneath disk Safeguard: ● When in operation, shaft concealed by base housing and unable to be touched Risk: Flying fragments if pin breaks Safeguard:

	• Cardboard shell immediately around apparatus • Charcoal cup may catch pieces beforehand • Fume hood stops pieces as last resort Risk: Charcoal dust particles • Damage to pin-on-disk's electrical components Safeguard: • Disk is not flush with the top surface to prevent charcoal dust from entering the base Risk: Ground charcoal could become airborne • Harm to lungs/eyes • Damage to nearby instruments Safeguards: • Eye goggles instead of glasses when operating the machine • Paper dust masks if necessary • Cardboard shell contains particles • Fume hood closed and venting particles Risk: Friction heat • Potential burning of charcoal Safeguard: • Fume hood contains charcoal and limits oxygen supply for fire Risk: Electrical parts and assemblies Safeguards: • Main electrical components will be housed inside base, away from fingers • Standard safety cord will be used to plug into the wall
Display	No risks, apparatus will be stored in plastic case, no need to turn on
Storage	No risks, apparatus will be stored in plastic case, also in a cabinet
Disposal	There are no risks to throwing charcoal away with normal trash. After testing, charcoal dust will be cleaned off the apparatus, wrapped in foil, and disposed of in a laboratory trash can.

3.6 Team management

As a small team, management was relatively smooth. Both members must attend all meetings with the project advisor, Dr. Sepehrband, and the secondary advisor, Dr. Hight. Both team members received training on the machines in the Mechanical Engineering Lab and were able to contribute to fabrication.

Other than designing the pin-on-disk testing machine, much of the early work involved communicating with different parties. Each member has people for whom they are the primary contact. Aaron is the primary contact for the MIT researchers, Ms. Wang and Mr. Sweeney; and Maureen is the primary contact for Betty Ikalany and AEST. This way responsibility for organization and follow-up has been more even and there is a consistent line of communication with each outside entity. Similarly, Maureen communicated with Chip Koehler, the industry advisor for the motor subsystem, while Aaron communicated with BJ Hamel, who advised on heat treatment and the likelihood of erosion and corrosion.

Maureen was the only student member who had machine shop certification during most of winter quarter, which drove the task breakdown for the quarter. By week 10 Aaron had lab certification and fabricated the disk holder subsystem using the mill and lathe. Maureen fabricated the rest of the apparatus and the pin specimens. Both students participated in sourcing the motor. Aaron did the stress calculations for finite element analysis.

During the spring quarter, Maureen did the preliminary testing to find the right speed and time for each pin-on-disk trial, as well as managed running the trials. Aaron formulated the equations for heat treatment and carried out the first heat treatments and quenchers. Maureen did the imaging of the specimens with the microscope and Aaron performed the Vickers hardness testing. Both students prepared specimens through epoxy mounting and surface polishing. Many of the lab tasks required the students to spend several hours in the lab monitoring machines, and attention was paid to make sure that this was shared in an equitable way, balanced with other tasks performed outside the lab such as report-writing and attending the SEEDS presentation day.

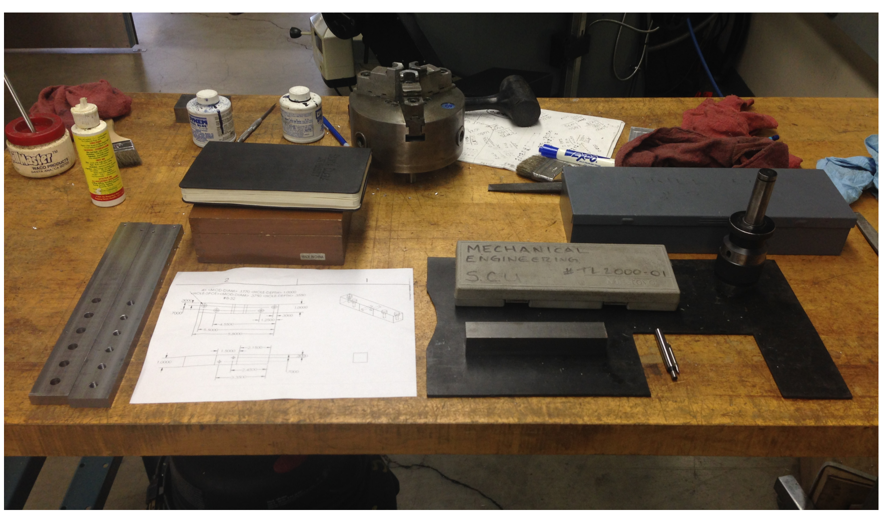

Figure 8 – Machine shop set-up for mill fabrication of vertical arm subsystem.

4 Subsystem Chapters

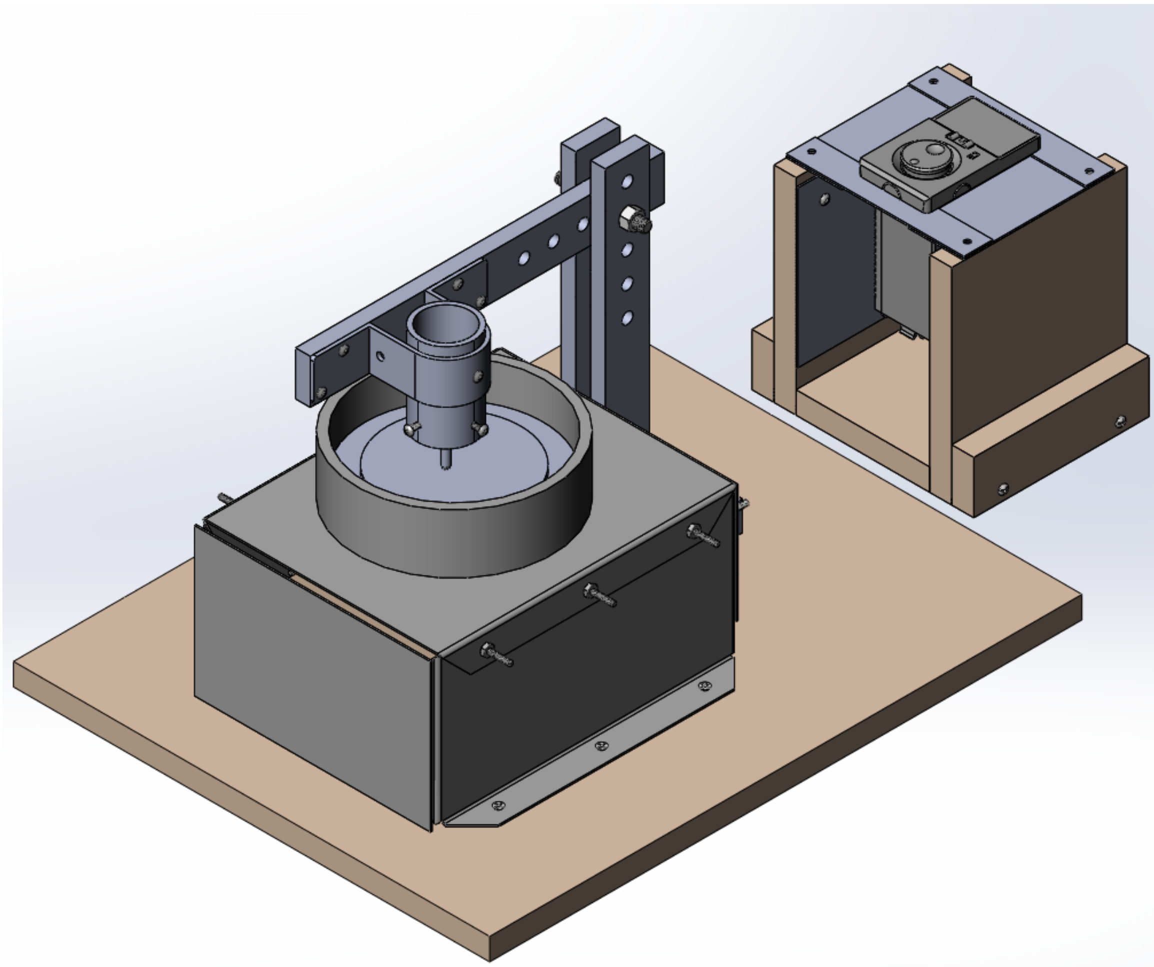

Figure 9 - CAD model of Pin-on-Disk Apparatus.

4.1 Frame and Load Application

The majority of the pin-on-disk apparatus is the frame, which must hold the pin and disk steadily in place while housing the electronic components underneath. This includes the arm that holds the pin directly over the disk, as well as the loading mechanism for pressing the pin and disk together. A good frame should:

- Minimize vibration for test consistency
- Allow height adjustment to accommodate different pin lengths
- Allow variable, easily adjusted and easily measured loads
- Maintain pin and disk stability over several hours unattended
- Be small and lightweight for portability

Three options were considered, starting with two main ideas: a standard single-arm apparatus and a more compact double-arm version. Within the single-arm concept, two further options were to have the disk spin under a stationary pin or to have the pin revolve over a stationary disk. The double-arm concept was made to improve the stability of a revolving pin design.

Ultimately a single-arm frame with a spinning disk was chosen. It rated the best on the scoring matrix, as seen in Table B 1 in Appendix B, especially in the very important area of vibration damping. Though not reflected on the scoring sheet, it also seemed easiest to construct compared to a less typical design. Furthermore, while its weakest area was allowing necessary charcoal to be applied during the test, the ratings for charcoal applicability were determined using an earlier, less feasible concept for charcoal application. The new charcoal application (explained in the charcoal subsystem chapter) works with a spinning disk design and makes this frame the clear choice.

The load mechanism had four main options under two general categories: use of weights, either through pulleys or by placing weights directly above the pin, and use of compression, either via a spring under the disk or a lead screw in the arm.

Ultimately the team did not end up applying any extra weight, using only the weight of the arm and pin holder since the main grinding action was between the pin and the surrounding charcoal. Nonetheless, in case additional load was needed, weights directly on top of the pin were chosen based on the scoring matrix in Table B 2 in Appendix B. This option prioritizes the very important qualities of straight and measurable loading, as well as simplicity. A simple, effective loading mechanism was very important for making the pin-on-disk machine easier to construct and troubleshoot, so direct weights made the most sense.

4.1.1 Vertical Arms

The vertical arms have 6 holes, as seen in Figure 10, to allow for different sized pins and to accommodate different sized motors, as these parts were fabricated during the search for the motor. The front arm has threading while the back arm does not, allowing for a more secure joint for the horizontal arm (with unthreaded holes) to rotate about. This pin joint can be seen in Figure 11. Ideally, both vertical arms would have internally threaded holes, but this was impractical to fabricate, as they would have needed to align perfectly. The vertical arms were attached to the feet with machine screws, and then the feet were screwed into the wooden base. A wooden base was chosen as it would not add too much weight to the final apparatus and is easy to attach other parts to.

4.1.2 Horizontal Arm

The horizontal arm and pin-holder was made of 3 components. The arm itself was made of aluminum, and has 5 un-tapped holes drilled along the length from the right edge in Figure 12. Finite element analysis was used to verify the safety of this hole placement, and can be found in Appendix F. At the left end of the arm was a modified fencing strap tie that holds which is attached to the arm using machine screws. The strap was modified by drilling a threaded hole at the front that more securely attaches the vertical tube. The vertical tube was made of aluminum and 3 threaded holes were drilled 2 cm from the bottom. Machine screws were inserted into these holes and tightened to hold the pin specimen.

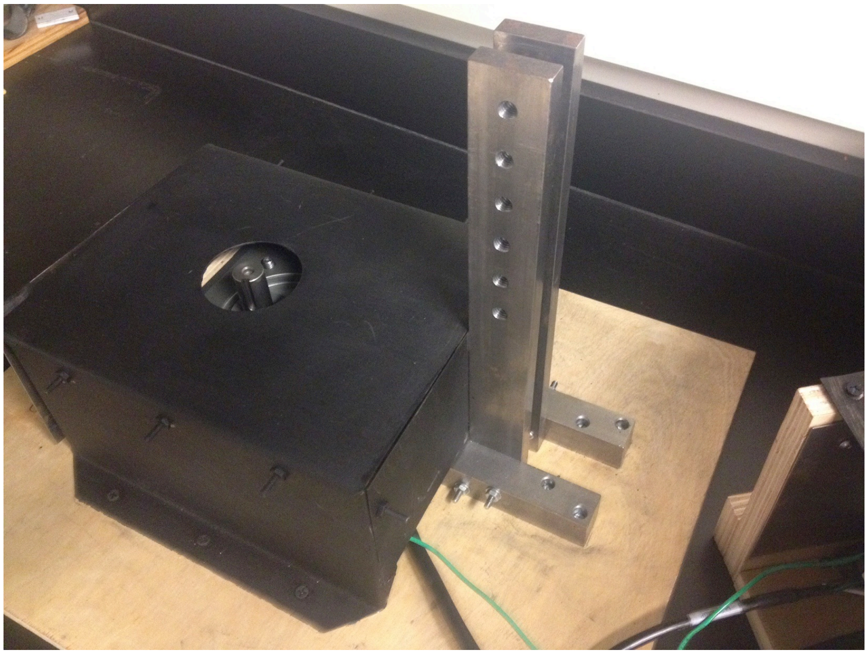

Figure 10 – Sheet metal frame painted black, motor shaft is accessible through hole in top.

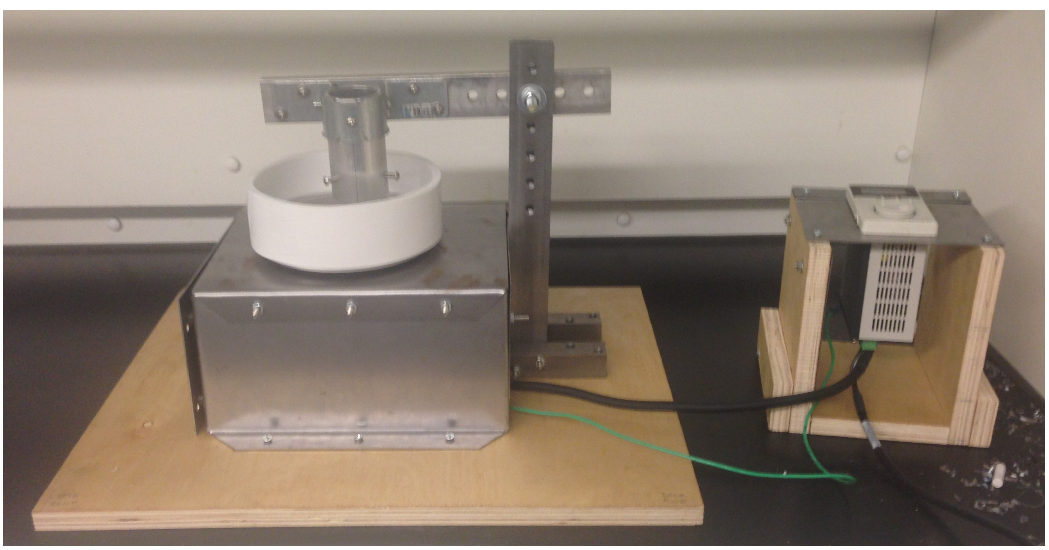

Figure 11 – View of complete frame assembly.

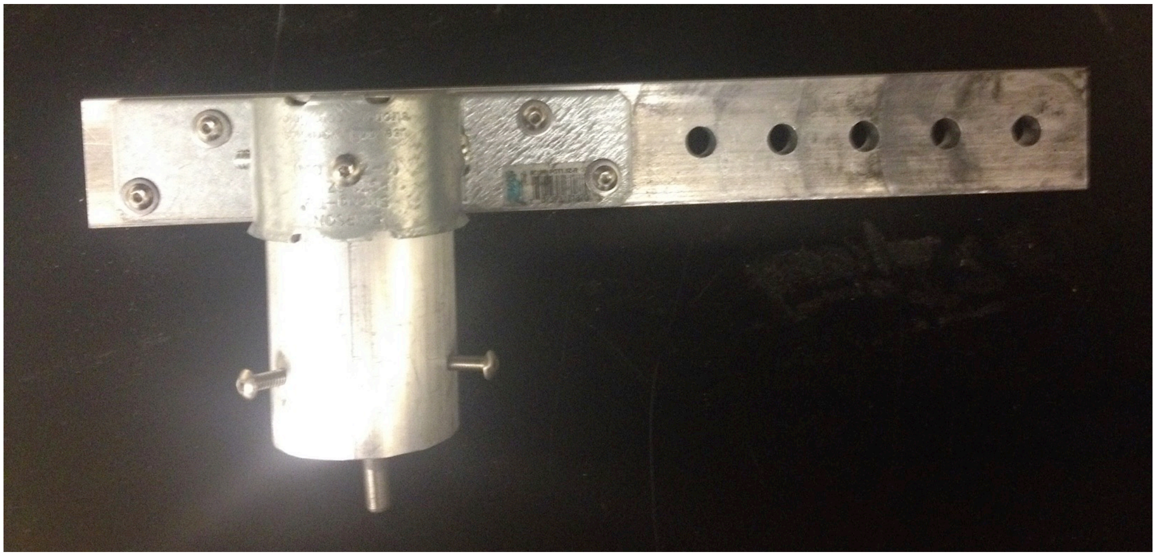

Figure 12 – Horizontal arm and pin-holder.

4.2 Electronics and Motor

The electrical components consisted of the motor, variable speed control, and power outlet.

The main motor need was the ability to run continuously for at least 8 hours and be able to plug into a normal wall outlet. A rated torque of 18 in-lb (2.0337 N-m) and an axial load of at least 9 lb (40.034 N) was desired, along with the ability to vary the speed between 60-600 rpm. Initially, the team purchased a used motor from a Buehler twin polisher grinder for $75. However, they were unable to access schematics or information about the motor that would allow them to safely connect it to a variable speed controller. For this reason, a new motor system was purchased.

The motor system purchased from Oriental Motor Co. consisted of a motor and driver. The model purchased was the BMU5120AP-5A-3 Brushless DC Motor Speed Control System which has a rated torque of 17.17 in-lb (1.9399 N-m) and a max axial load of 33 lb (146.791 N). As the estimates for torque were calculated with a 3x factor of safety, 17.17 in-lb (1.9399 N-m) was considered sufficient. The motor can vary in speed from 16-800 rpm and has a high dust protection rating. The motor system came with a controller and was connected using the pin connectors on the supplied wires and also additional ground wires. The system was plugged into a normal wall 110V wall electrical socket that is on the sides of the fume hood.

Figure 13 – Top and side views of driver support structure.

4.3 Charcoal Distribution

It was very important to have charcoal dust on the surface of the disk to simulate wear. Initially, a stationary disk and spinning pin apparatus was considered in order to allow the charcoal dust to sit on a flat disk without flying off. Various methods of charcoal distribution were considered, as seen in Table B 3 in Appendix B, but they were cumbersome and inelegant. One of the most promising solutions was to construct a tube around the pin where charcoal could be deposited, but this was still rather complicated. The main concern was that an application system with moving parts would not be robust enough to run for 8 hours unsupervised.

After investigating how other groups have added outside materials to pin on disk testing, the idea was formed to have a cup shaped disk instead of a flat one, so that the charcoal would not fly away. The bottom of the cup was made out of stainless steel disk that locked into an aluminum base. The sides of the cup were cut from a schedule 40 6 in (15.24 cm) ABS plastic pipe. Figure 14 shows a conceptual drawing of this system.

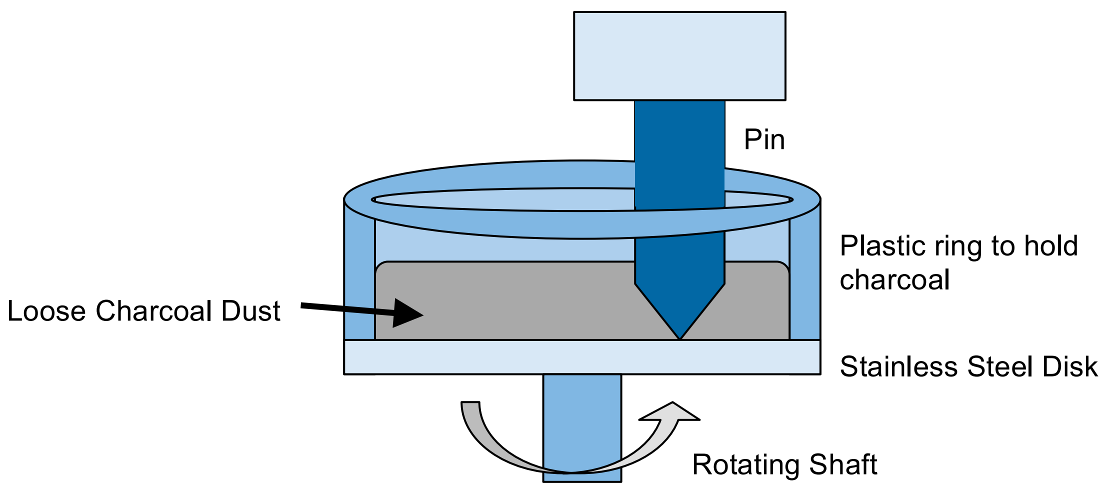

Figure 14 - Charcoal Application Subsystem, final conceptual design.

There are many benefits to this charcoal application method:

- Ease of construction
- Closest to auger conditions in extruder
- Mitigates charcoal dust being flung off the disk during rotation
- Provides a safeguard should the pin break during testing

4.4 Disk Subsystem

4.4.1 Support Plate and Locking Mechanism

The locking mechanism was modeled after the plates used on the polishers in the materials lab. It consists of three raised cylinders on the aluminum plate, which fit into three cylindrical bore holes on the stainless steel disks to keep them in matching rotation. The central cylinder was created by cutting away material around it using a lathe. Two holes were then milled into the plate where the remaining cylinders would go and then they were filled with cylindrical plugs of nearly the same diameter for a secure press fit.

4.4.2 Disk Fabrication

While the final disks were made of stainless steel by the outside source Parametric Manufacturing following the team's drawings, the design was first tested and slightly modified with an aluminum disk made in the SCU machine shop. A simple automation program was used with the mill to carve out the holes in locations matching the cylinders on the supporting plate. The diameter of the holes was gradually increased through repeated trials until the disk could easily slip on and off of the plate.

4.4.3 Drive Shaft

The drive shaft connecting the supporting plate to the motor's rotation was made from a part of the unused Buehler motor for efficiency, although future versions could use a simple aluminum cylinder. The hole inside the reused drive shaft was widened to fit the Oriental motor's shaft and given a keyway matching the motor's provided key. To attach it to the supporting plate, holes were drilled all the way through the drive shaft and partway through the plate for screws to secure them together. A small depression was also carved out of the plate bottom with a lathe to ensure a consistent fit.

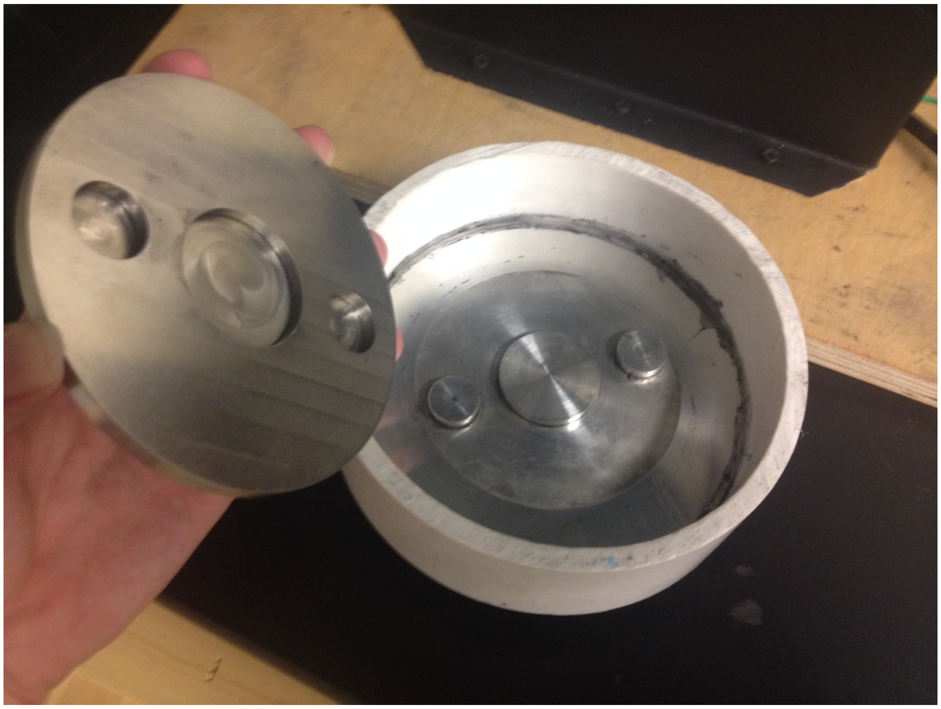

Figure 15 – Locking mechanism in disk subsystem.

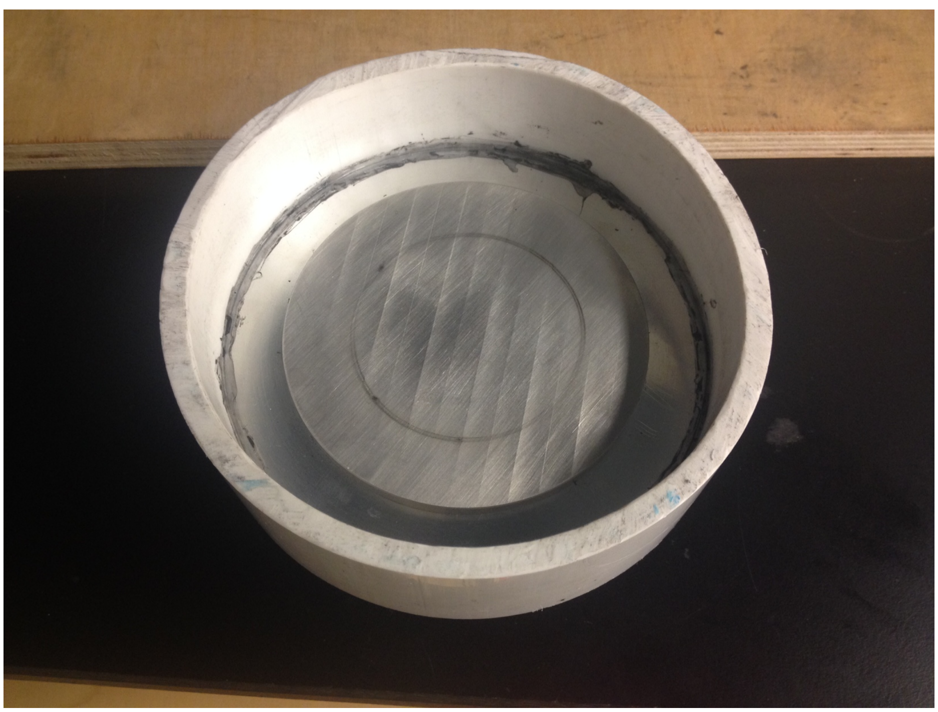

Figure 16 – Assembled disk subsystem

5 System Integration and Testing

5.1 Heat Treatment Procedures

The team used pack carburization to case harden pins of 1018 steel. This was done to give them a hard, erosion-resistant outer layer while leaving the interior soft. This method was of particular interest for investigation since an auger needs a soft core in order to flex and avoid breaking during the extrusion process. Using case hardening for AEST's augers was thus a promising possibility to test, especially because they have already performed some case hardening with their on-site furnace.

The team carburized a total of 11 samples, 10 of which were used for the final set of results. Other than the first attempt, the pins were all heat treated in pairs, one quenched in water and the other in oil. Table 9 shows the time, temperature, quenchant, and expected case depth for each heat treatment performed.

Table 9 - Heat treatments applied to pins of 1018 steel.

Temperature (°C)	Time (hours)	Quenchant	Expected Case Depth (in)	Expected Case Depth (cm)
975	1.8	Water	0.02	0.0508
975	1.8	Oil	0.02	0.0508
1000	3.1	Water	0.03	0.0762
1000	3.1	Oil	0.03	0.0762
1025	3.5	Water	0.036	0.0914
1025	3.5	Oil	0.036	0.0914
1025	4.3	Water	0.04	0.1016
1025	4.3	Oil	0.04	0.1016
1000	9.2	Water	0.045	0.1143
1000	9.2	Oil	0.045	0.1143

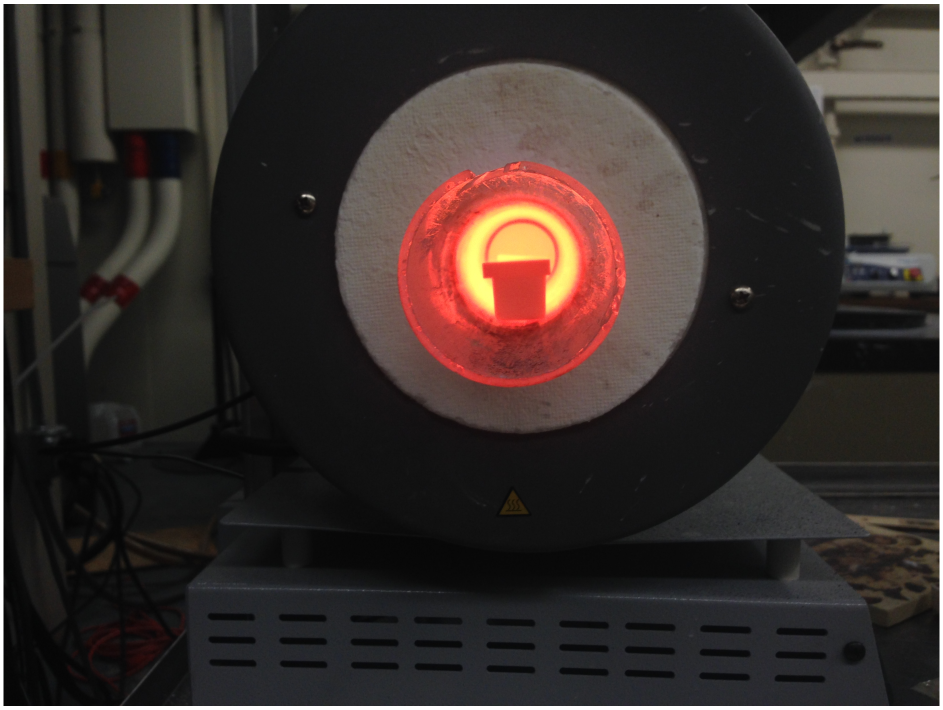

Figure 17 – Pin specimen in a crucible in the materials lab furnace.

5.2 Pin-on-Disk Experimental Protocol

5.2.1 Pin Fabrication

Pins were fabricated from cold rolled steel round stock of different diameters, based on availability. The 1018 and 1214 steel was 0.3125 in (0.7936 cm) in diameter, the 1045 steel was 0.5 in (1.2700 cm) in diameter, and the 8620 steel was 0.4375 in (1.1113 cm) in diameter. The variation in diameter did not affect the results as the tip was rounded and the wear was measured through mass loss. The 1018 steel was chosen to represent the recycled mild steel that AEST uses in its augers, and the other steels were chosen as benchmarks to gauge the improvement in heat treatment, as well as investigate the effects of different types of steels.

First, the stock was cut to 4 in (10.16 cm) lengths using a vertical band saw. This length represents two pins, and was done for easier handling. Then each side of the stock was fabricated using the lathe on speed 1100 rpm.

Several pins were fabricated using 1018 stock and had poor surface finish. Various methods were tried to improve the surface finish, such as sanding with steel wool and different grit sandpapers, however this still left an unsatisfactorily rough surface. It was postulated that the stock was not true, and perhaps initially doing a cut of 0.001 in (0.00254 cm), similar to a finishing cut, would make the stock true and ready for fabrication. Performing this initial shallow cut did in fact produce a much better surface finish than the initial pins.

A sequence of cuts was then determined to provide the best surface finish:

1. Remove 0.0050 in (0.0127 cm)
2. Remove 0.0050 in (0.0127 cm)
3. Remove 0.0100 in (0.0254 cm)
4. Remove 0.0050 in (0.0127 cm)
5. Remove 0.0050 in (0.0127 cm)

This methodology produced pins that had a better surface finish than those that had been polished with steel wool or sandpaper. Next, the tip was rounded to a ball tip using a file. Rounding with a file worked better than with sandpaper or steel wood as more pressure could be applied. This process was repeated on the other side of the 4 in (10.16 cm) stock and then the stock was cut in two leaving 2 pins of 2 in (5.08 cm) length.

Next, the pin specimens were mounted in 2-part epoxy in order to make them easier to handle. The larger diameter of the epoxy mold allowed for a better grip from the three screws inside the pin holder. Mounting specimens that extend 1 inch (2.54 cm) from the surface of the epoxy is unusual, however it worked well for this application.

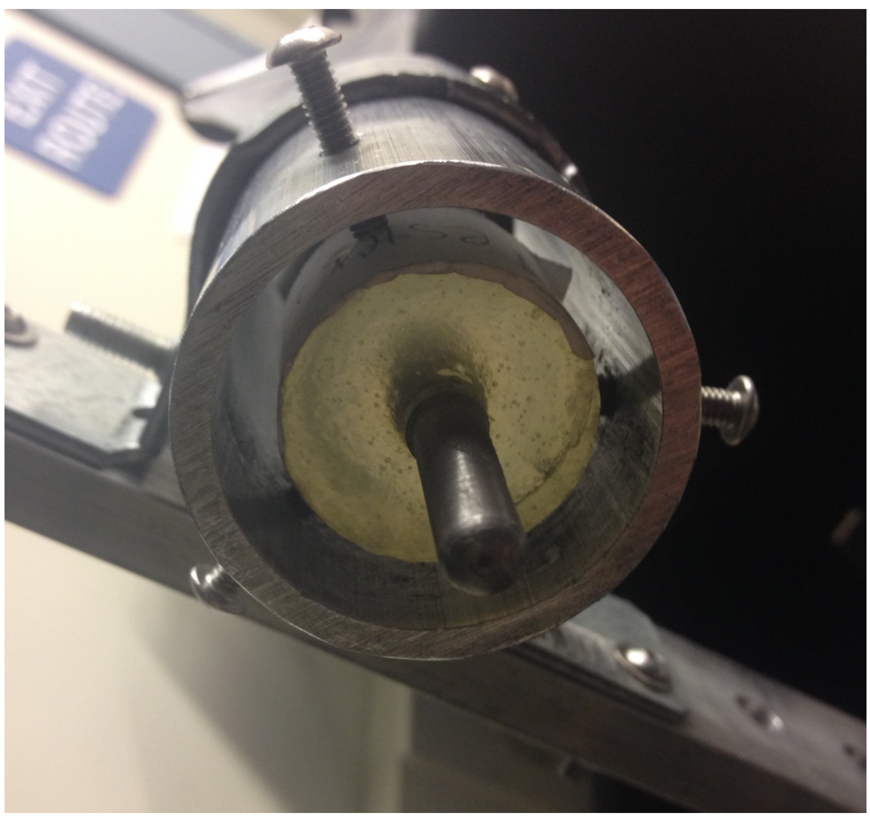

Figure 18 – View from below pin holder that shows epoxy-mounted pin held by 3 machine screws.

5.2.2 Testing Specifications

The first two pin specimens inserted into the apparatus were used to test the trial conditions. The first pin was run at 400 RPM without charcoal for 8 hours to ensure that the machine would reliably operate for 8 hours. The second pin was run at different RPMs with charcoal dust in the cup to find a reasonable speed that would not cause too much charcoal dust to be flung from the cup. A speed of 300 RPM and a trial time of 5 hours was chosen as this allowed for a visible wear pattern as well as the ability to run multiple tests in one day. All trials were run with the arm pin joint in the last hole on the horizontal arm as this provided the largest wear track radius.

5.2.3 Sample preparation

In addition to the 1018 pin specimens, 0.5 in (1.27 cm) process control specimens cut from the same round stock were placed in the crucibles and case-hardened at the same time. These samples were then mounted in epoxy and the surfaces were polished using the polisher in the materials lab. After the surfaces were smoothed, these process control specimens underwent Vickers hardness testing to ensure the pieces were properly case hardened.

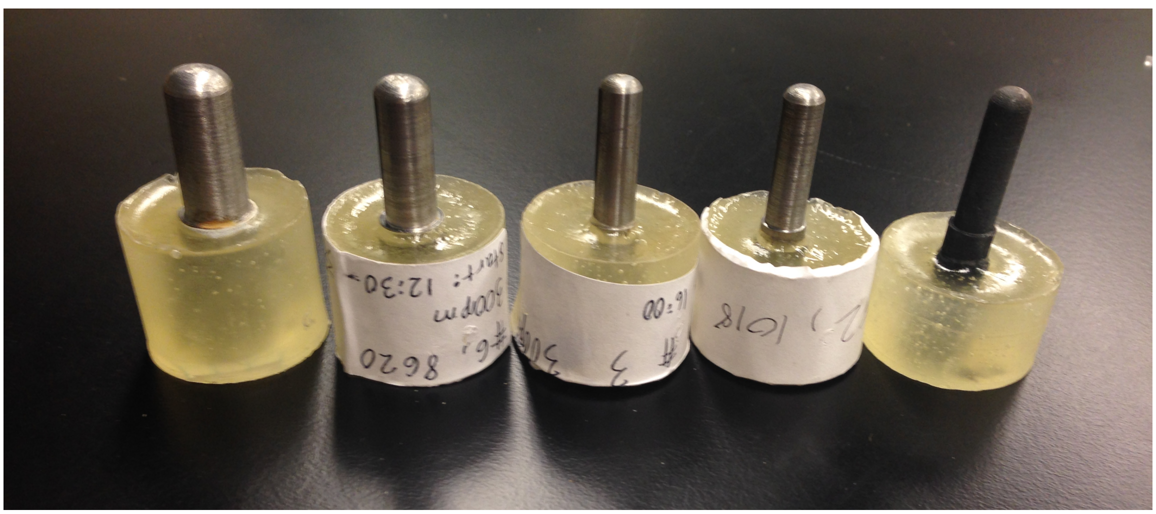

Figure 19 – Various mounted pin specimens.

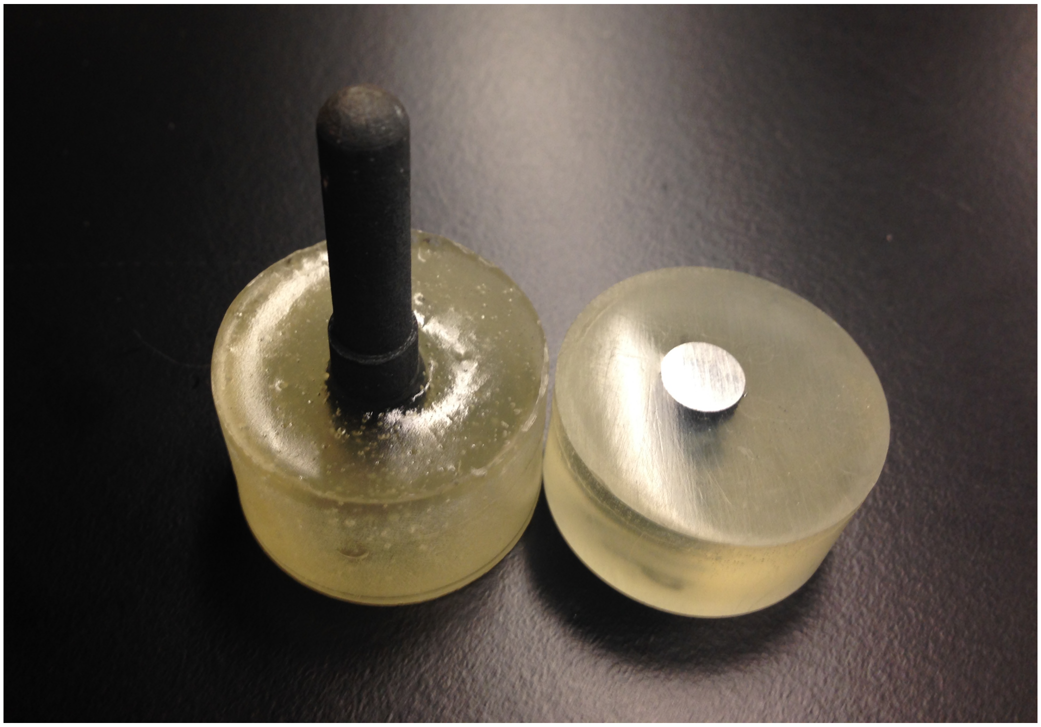

Figure 20 – Mounted case hardened pin specimen and process control specimen.

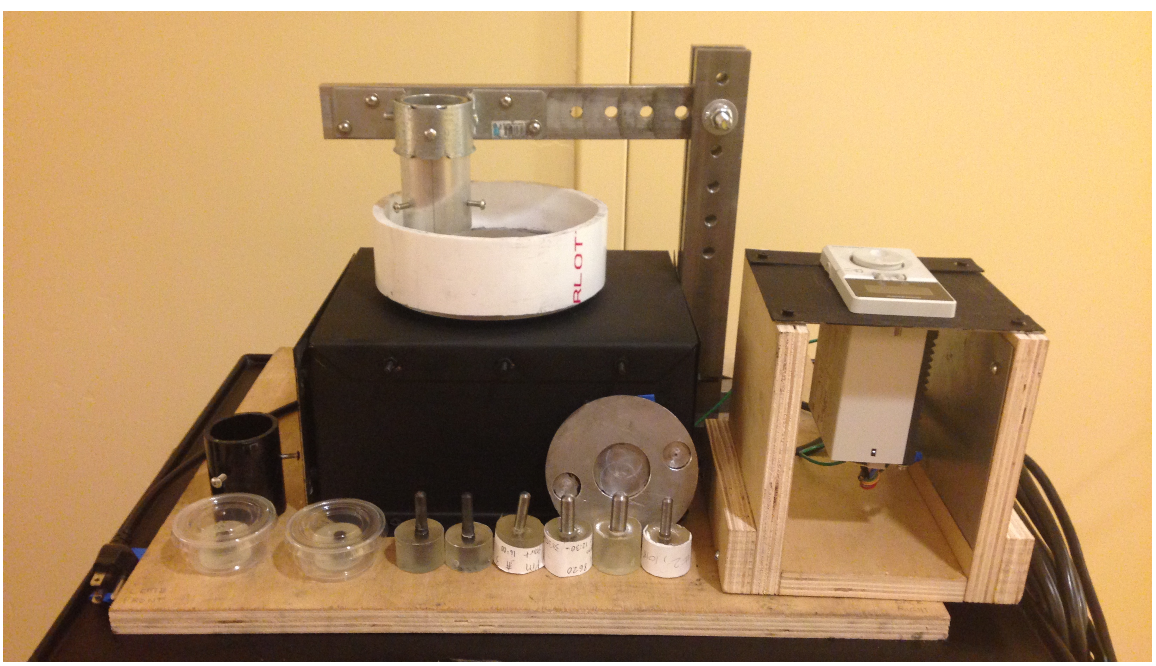

Figure 21 – Mounted pin specimens and apparatus.

5.3 Results

5.3.1 Imaging Results

Looking at the pin specimens under a microscope showed that the primary wear mechanism was three body abrasion, as compared to examples found in *Friction, Wear, and Erosion Atlas.* The three bodies in this experiment are the pin, the disk, and the charcoal particles. Three-body abrasion is characterized visually by long striations and random breaks. In Figure 22, the striations can be observed extending from the top left corner to the bottom right corner.

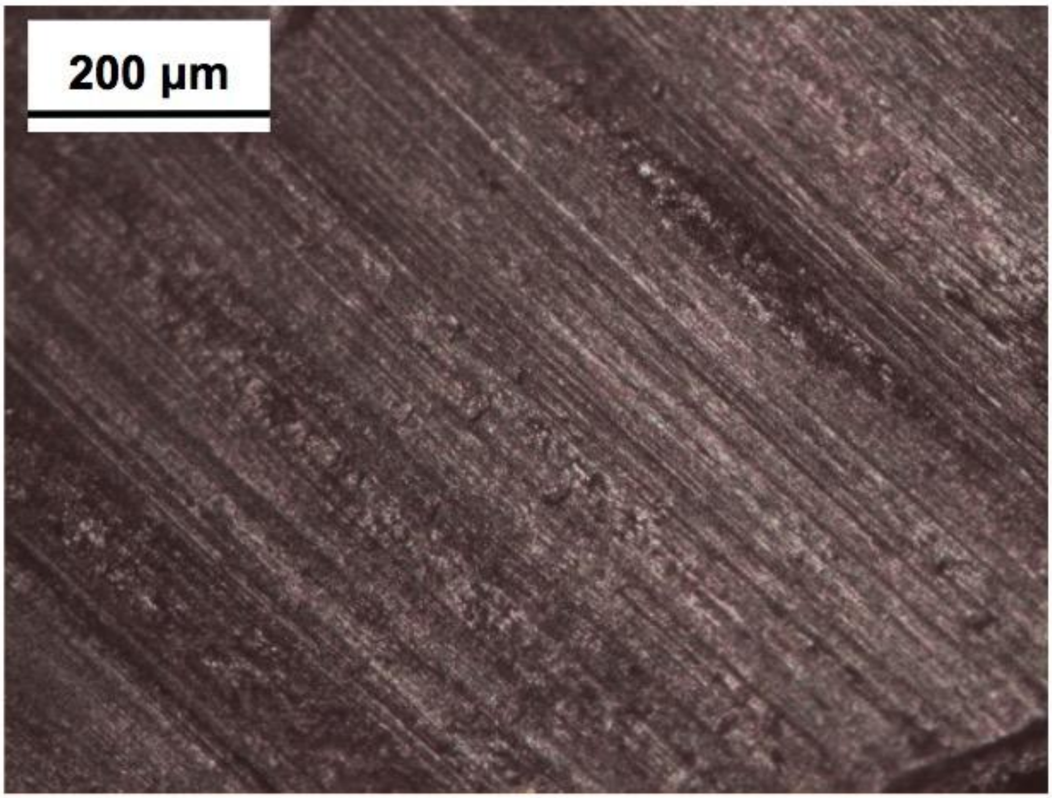

Figure 22 - Untreated 1018 steel and ground charcoal, 100x, showing three-body abrasion.

Some specimens exhibited what looked like pockmarks under the microscope, however these are from the construction of the pins—rather than signs of corrosion—as they were not shown on all specimens. These pockmarks can be seen in Figure 23. Complete imaging results can be seen in Appendix G.

Figure 23 - Example of pockmarks on heat-treated sample [case depth: 0.0508 cm, oil quenched], 5x.

Figure 22 and Figure 23 have re-colored to more accurately represent the color seen by eye. The figures in Appendix G have not been re-colored, and the orange coloring is due to the microscope light.

5.3.2 Microhardness Results

Vickers microhardness tests were performed on smaller cylindrical samples (process control samples) case hardened in the same crucibles as their corresponding pins to match their heat treatment conditions. The indentations were made starting from the center and proceeding toward the edge of the polished cylinder face to measure any difference in hardness given by the heat treatment. This was repeated in up to 7 directions for each sample to give a thorough average hardness at each distance from the center. A higher hardness was expected near the edge of each sample as an indication that case hardening had worked.

Figure 24 shows one sample's graph of hardness with increasing distance from the center. The hardness does increase near the edge as expected, a good indication that heat treatment had taken effect. Full hardness results can be seen in Appendix G.

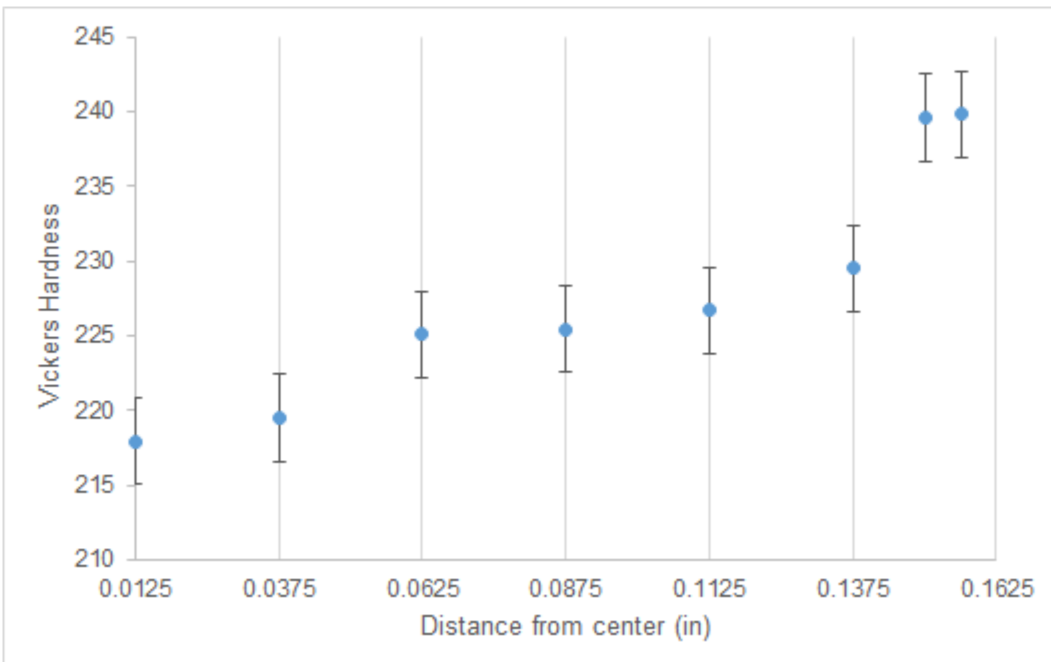

Figure 24 - Hardness of 0.0762 cm case depth sample from center to edge.

5.3.3 Mass Loss

Table 10 shows the mass loss results of the pin-on-disk testing trials. Figure 25 shows this information in a bar graph.

Table 10 - Mass loss of different pin specimens after undergoing pin-on-disk testing at 300 RPM for 5 hours

Pin Base Metal	Depth of Heat Treatment (cm)	Quenchant	Mass Loss (g)
1018	-	-	0.1680
1214	-	-	0.1086
1045	-	-	0.0170
8620	-	-	0.0127
1018	0.0508	Water	0.0550
1018	0.0508	Oil	0.0714
1018	0.0762	Water	0.0342
1018	0.0762	Oil	0.0421
1018	0.0914	Water	0.0205
1018	0.0914	Oil	0.0298
1018	0.1016	Water	0.0119
1018	0.1016	Oil	0.0108
1018	0.1143	Water	0.0050
1018	0.1143	Oil	0.0047

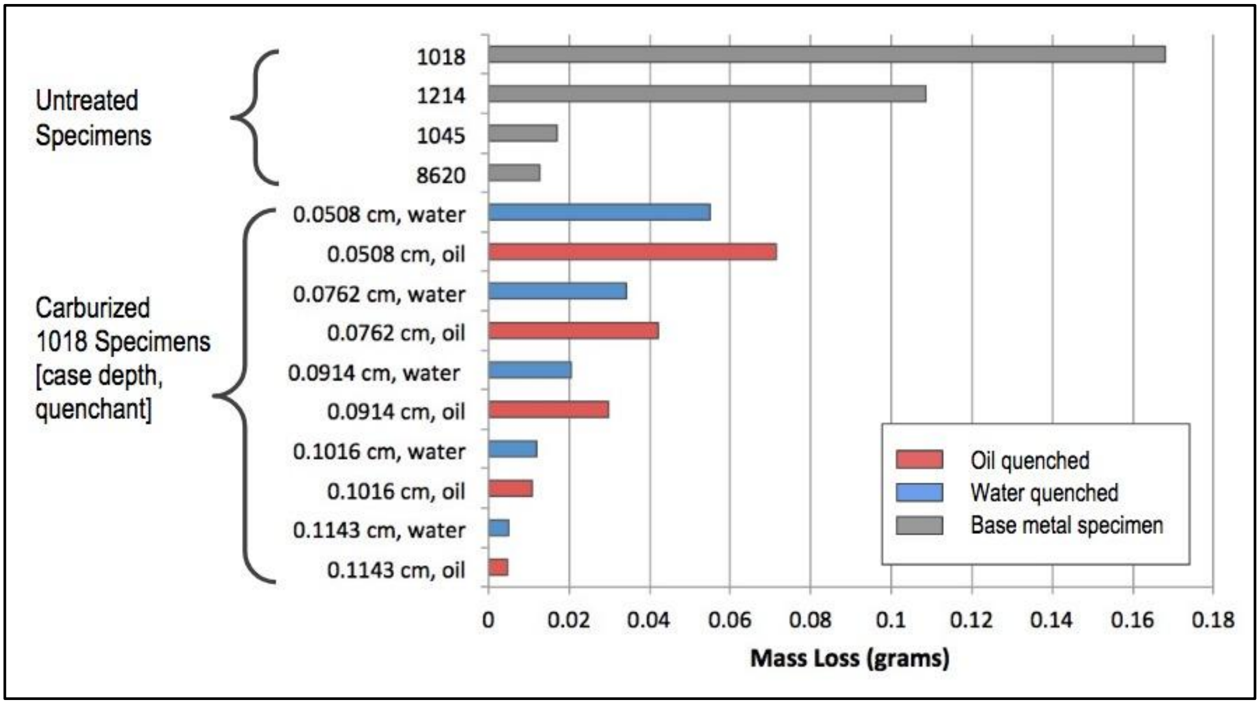

Figure 25 - Bar graph showing the mass loss in grams of different pin specimens after undergoing pin-on-disk testing at 300 RPM for 5 hours.

There are several trends in Figure 14 that should be noted. Looking at the carburized specimens, the general trend is that a higher case depth leads to a decrease in mass loss and therefore an increase in wear resistance. For lower case depths, water-quenched specimens exhibited less mass loss due to the relative severity of water quenching versus oil quenching. However, as the case depth increased, this difference became negligible. This is because as case depth increases, the metal becomes less sensitive to the kind of quenching media.

5.3.4 Base Metal Comparison

Although AEST expressed preference for improving their current method of case hardening rather than finding a new material, the costs and tradeoffs of 1045 and 8620 steel were explored as they showed similar wear resistance properties to case hardening 1018 steel to a depth of 0.1016 cm.

1045 steel seemed like a promising alternative, however based on interviews with AEST and the D-Labs the cost of the raw materials for a 1045 steel auger would likely be 50% more than the costs of the 1018 steel auger, based on the prices of metals regularly found in the Kampala scrapyard where AEST sources their raw materials. 1045 steel, due to its high carbon content, is more brittle than 1018 steel, and the effects of this increased brittleness are unknown, while case hardening is a somewhat more proven solution. 1045 can also not be case hardened, so while a 1018 auger could be repaired multiple times, thus extending its lifespan, 1045 cannot. 8620 steel is not regularly available in the Kampala scrapyard and is therefore not a god alternative, and like 1045 steel it cannot be case hardened.

5.3.5 Heat Treatment Comparison

Although, as expected, the case depth of 0.1143 cm provided the least mass loss, it would take over 7 hours at 1025 ˚C to case harden to this depth. As the normal AEST work day is only 5 hours, this length of time is likely not feasible. A case depth of 0.1016 cm can be achieved in 4 hours and 20 minutes at a temperature of 1025 ˚C. Due to the imprecise temperature measurements done in the field [2], it is prudent to case harden for as long as possible in order to maximize case-depth.

The use of oil as a quenchant results in a less severe quench than water. Oil quenching results in less residual stresses on the sides and ends of disk specimens. Although it is difficult to estimate distortion on pieces such as the augers, which have non-uniform shape, oil quenching will lead to less distortion than water in this case as well [12]. As the depth of case is deepened, the quench media has less effect on the wear resistance. At the desired case depth of 0.1016 the differences are negligible.

5.3.5.1 Eco-Audit Analysis

To confirm that the best-performing options would be viable for AEST to implement, the team used the material database software CES EduPack 2016 to compare several materials' energy and monetary costs. The program's Eco Audit feature was used with the Level 3 database to see the most specific material information available with Santa Clara's license. Figure 26, Figure 27, and Figure 28 show the resulting Eco Audit charts.

The primary motivation for the audit was to compare AEST's current heat treatment of 0.02" (0.0508 cm) case depth to the team's favored option of increasing to 0.04" (0.1016 cm) case depth. Other solutions like switching to 1045 steel and 8620 steel were also included in the audit, although these were less representative since the program's database lacked country-specific material costs for the vast majority of Africa. The audit was overall more useful for comparison than absolute numbers due to the generic information and estimation involved.

The team set up the audit to simulate the costs of acquiring and treating the augers over the course of one year. The material with the lowest mass loss, 1018 steel heat treated to 0.04" (0.1016 cm) case depth, was used as a baseline for the number of augers required over the year. The pin-on-disk mass loss data was then used to multiply the number of augers needed throughout the year for the other materials. The Use cost accounted for the added cost of burned charcoal for the heat-treated samples.

Most important from the audit is the confirmation that AEST increasing their heat treatment depth will not increase cost since they will need far fewer augers in the same amount of time. While the audit also shows that using harder steels cost very nearly the same as increasing case depth, the team still favors heat treatment since the database does not reflect the rarity of other steels in Uganda.

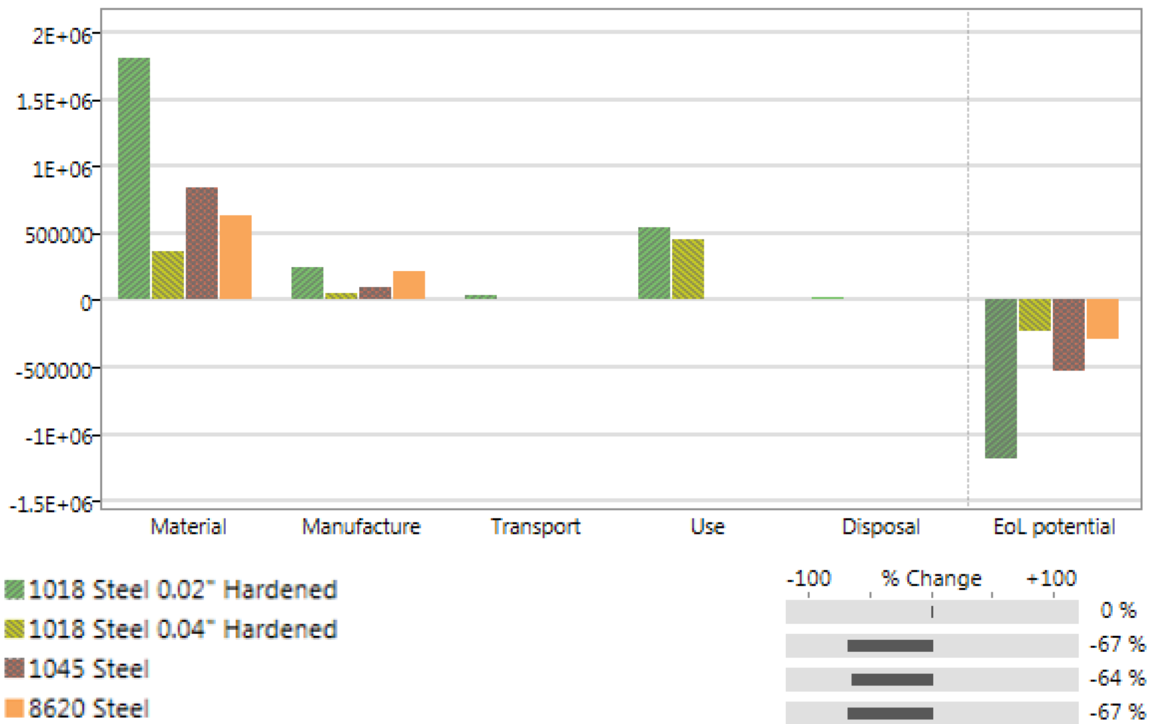

Figure 26 – Energy (kcal) costs comparison of different auger materials using EduPack software.

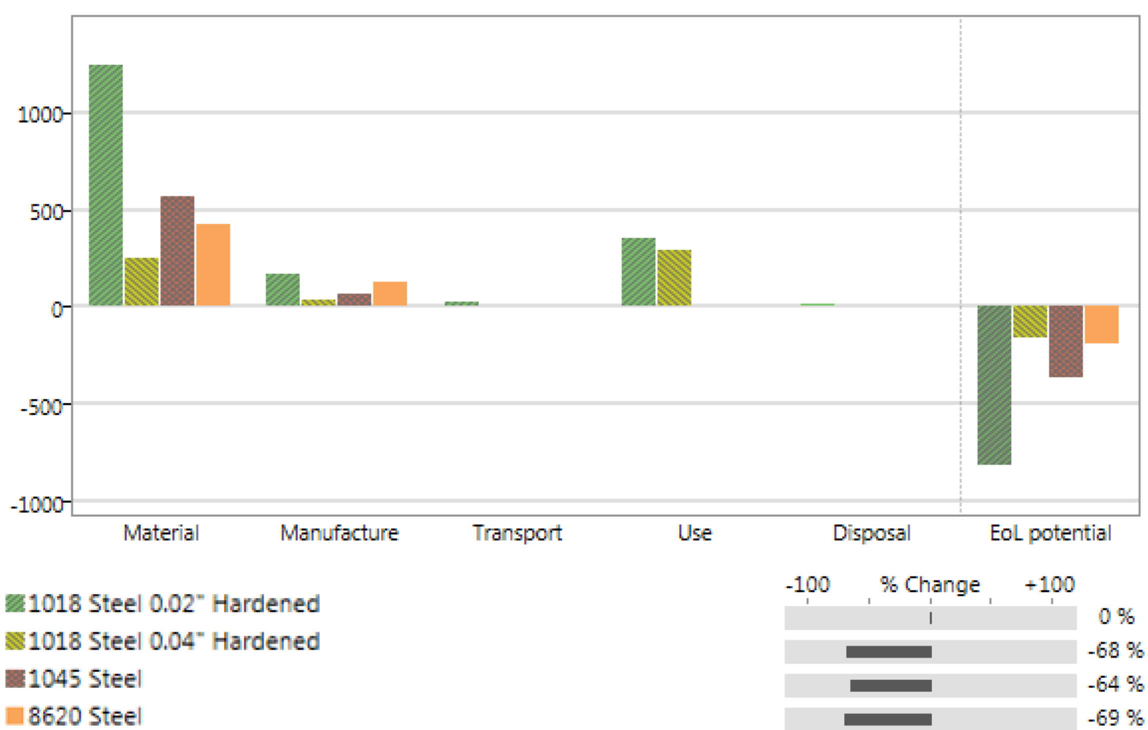

Figure 27 – CO2 footprint (lb) comparison of different auger materials using EduPack software.

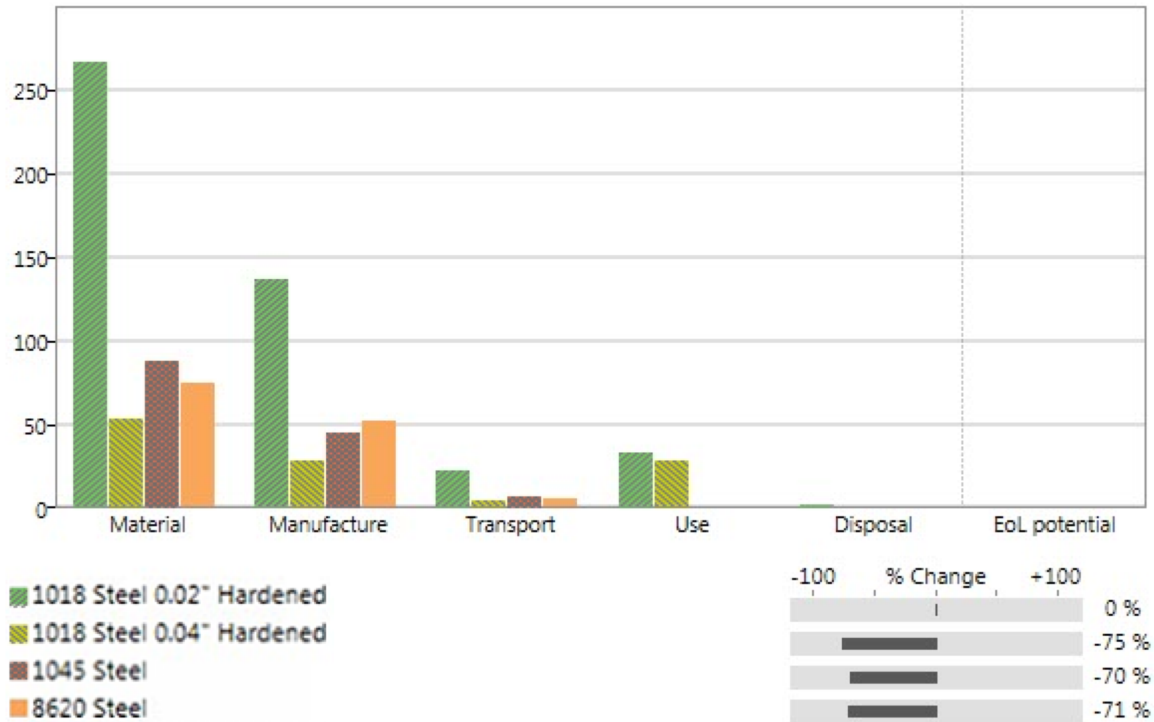

Figure 28 – Cost (USD) comparison of different auger materials using EduPack software.

5.3.6 Suggestion to AEST

Currently AEST case hardens their augers to a depth of 0.02 in (0.0508 cm) and uses water quenching. The team's final suggestion was to switch to a case depth of 0.04 in (0.1016 cm) and switch to oil as a quenchant. In laboratory testing, this change led to an 80% increase in wear resistance, from a mass loss of 0.55g to a mass loss of only 0.0108g. The increased fuel costs associated with longer case hardening are offset by the increase in lifespan, and quenching oil can be reused many times.

6 Costing Analysis

The proposed was that $1500 would go toward the materials needed to build a pin-on-disk testing machine for the first stages of the project. Another $1500 would be needed for consumable supplies during testing. $500 was set aside to pay for a contractor to apply coatings to sample, however this was not accomplished due to time constraints. $500 was set aside for miscellaneous or unexpected charges. An ambitious travel budget of $2000 was projected to send both team members to a humanitarian engineering conference to present the results at the end of the project.

The group applied for the Roelandts Grant requesting $5000 (all except transport for one team member) and received $4000. The team also applied for the general senior design grant from the School of Engineering, and received $1000. This was used to cover funds not provided by the Roelandts Grant, as well as potentially allow one student to travel to conferences.

The team did not have sufficient time to explore coating options and have samples commissioned. However, the team believes that heat treatment is ultimately a better solution than coating as it can be done in-house by AEST. These extra funds allowed for the purchase of an analytical scale, which was necessary to take the mass of the pins before and after testing.

The team spent $950 on fabricating the apparatus, $1405 on testing and heat treatment supplies, and $1400 on an analytical balance. The total expenditures are currently $3750. The team plans to present at the IEEE (Institute of Electrical and Electronics Engineers) Global Humanitarian Technology Conference in October 2017. The abstract has been accepted and the paper will be submitted June 17th, 2017. The fees for the 2017 conference registration have not yet been released. Based on the 2016 fees, the projected registration cost for both team members will be $1200. This brings the projected expenditures to $4955. A comparison of the budget income and expenditures can be seen in Table 11.

Table 11 – Comparison of project budget and expenditures.

Category	Budget ($)	Expenditures ($)	Difference ($)
Apparatus	1500	950	+550
Testing Supplies	1500	1405	+95
Sample Coatings	500	0	+500
Miscellaneous	500	1400	-900
Conference Fees	1000	1200	-200
Total	**5000**	**4955**	**+45**

7 Business Plan

This section details a hypothetical plan for commercialization of the team's pin-on-disk apparatus as the fake company Scholastic Instruments.

7.1 Introduction

Scholastic Instruments (SI) is a small company based in the Bay Area that designs and sells low-cost and user-friendly materials testing apparatuses and equipment to be used in an undergraduate educational setting. The company will begin its product line with a pin-on-disk machine and will expand into other apparatuses in the future. The primary market is small-to-medium colleges with undergraduate engineering programs that do not have dedicated materials science laboratories. The secondary market is high schools, hobbyists, and other science educational programs for youth. There is no affordable materials testing apparatus company currently in operation, however the industrial competition is Koehler Instruments, headquartered in New York. At present, many smaller labs or educational spaces design and fabricate their own pin-on-disk apparatuses because there is no reasonably affordable option. SI aims to fill this gap.

7.2 Company Goals and Objectives

The company, Scholastic Instruments, will provide materials testing solutions to small to medium sized universities and colleges that may not have the funding or space requirements for an industrial-grade materials testing laboratory for undergraduates. Focusing on modularity and ease of use, SI will help bring materials science to more students. The importance of hands-on experience with quality laboratory equipment cannot be understated. The product line will begin with a low-cost pin-on-disk machine and later expand to other testing and sample preparation equipment. When possible, the apparatuses will be sent out as kits that can be assembled with a screwdriver.

7.3 The Product

A pin-on-disk machine, as the name suggests, consists mainly of a small cylindrical pin held in contact with a disk. A motor spins the disk so that the two pieces grind together for a set number of hours. The pin and disk are weighed before and after the testing so that the user can determine how quickly the two materials lose mass.

Pin-on-disk apparatuses are simple but effective tools for engineers, scientists, and students to quickly simulate what happens to materials under real-world conditions. Wear information from these machines is the starting point for any project group to solve problems through materials science.

In addition to the single setup of the motor, housing, and other structural equipment, the pin and disk need to be switched out to perform different material tests. SI will separately sell a variety of compatible pin and disk specimens to be used in the apparatus (five materials of each). These will be a source of renewable revenue from each single machine sale.

7.4 Potential Markets

The ideal SI customer is a small to medium college that offers courses in materials science but does not have a dedicated degree program in the subject. Industrial grade materials testing equipment is often prohibitively expensive, and prevents these programs from growing, as students do not have access to the equipment needed to do meaningful experiments. According to the College Board there are only 40 U.S. colleges that offer a dedicated B.S. in materials science and there are 250 small-to-medium colleges that have undergraduate engineering programs. Assuming that all colleges that offer an undergraduate degree in materials science also offer some sort of undergraduate engineering degree, this leaves a potential market of 210 schools. While many of these schools may currently have some materials science equipment, they probably do not have multiples of the same machines, which limits how many students can use them. SI looks to decrease the cost and complexity of materials science testing equipment to allow more students to gain valuable laboratory experience.

A smaller secondary market would be high schools, hobbyists, and STEM-focused after school programs and summer camps. While this market will likely be much smaller, it is important initially in order to increase awareness of SI's product line.

7.5 Competition

There are no similar items on the market today. Colleges looking to expand their material science laboratories either must buy industrial equipment or make the apparatuses in house. While a fully custom apparatus can have benefits, the time

The primary competition would be companies like Koehler Instruments (KI), that manufacture and sells petrochemical and materials (metals) testing equipment. KI was founded in 1935, has 50-100 employees, and an estimated annual sales of $10-24.9 million according to ThomasNet's company profile. KI sells a pin on disk testing machine, product number K93500. While the K93500 can perform all the functions that SI's pin on disk tester can, the SI model will have several key benefits. The exact price of the K93500 is unknown as the team was unable to obtain a quote from an online seller, but it is likely around $6000, while SI's model is $2000. The K93500 weighs 440 lbs (200 kg) and SI's model is only 25 lbs (11.5 kg). The smaller size, weight, and cost make SI's model a better solution for materials testing in an educational setting.

7.6 Marketing Approach

7.6.1 Advertising

SI will start advertising through Google Shopping in order to appear easily to students and schools in need of affordable wear testing equipment. Google Shopping's costs are highly versatile, and since each school will only need one or two of the product, this advertising cost need not be high.

Appearing in Google advertisements on other web pages is significantly more expensive in return for the greater exposure. Since the company anticipates that most customers will be ready to search on Google Shopping rather than only browsing related pages, this is an option to look into after profits have started.

Materials testing equipment prices are not readily available, with most sellers requiring an emailed quote request rather than readily providing pricing information. This can be frustrating and time consuming for a small lab or department attempting to compare prices. SI's pricing will be readily available on product pages. SI's transparent pricing structure will help it stand out from other manufacturers, and clearly show its lower prices.

SI will also showcase the apparatuses at technology fairs and shows such as Maker's Faire and the Bay Area Science Festival. Primary and secondary school educators and people doing hobbyist experimentation often attend these fairs. While these groups are not SI's primary target market, they represent a valuable secondary target market.

7.6.2 Stockists

In addition to selling directly though SI's website, SI will also sell through regional laboratory supplies stores, such as LabPro in Sunnyvale. This avenue will be piloted in the Bay Area where SI is headquartered, then expanded to other regions in California and eventually the US. Special focus will be given to areas with a high density of colleges, such as New England, to maximize potential clients served by a single laboratory supply store.

7.7 Manufacturing Plans

Scholastic Instruments will outsource the machining to KLH Industries, which supports monthly manufacture, management, and delivery of parts. Diamond Precision Products will be a backup source for cost-effective machining. SI will begin with eight machines per month for the first three months to build up a reserve of kits and spare parts. From there production will stay at four per month to maintain the supply as sales pick up during the school year. After nine months of school, pin-on-disk production will slow to two per month as the number of unsupplied target schools shrinks and SI begins production of other machines.

SI will also have extra pins and disks manufactured in addition to the starter samples that come with each kit. Since these need to be made of a variety of materials, 50 pins and 10 disks will be made each month for the first few months. This will increase as the number of machines sold and thus demand increases, with a small decrease during less busy summer months.

7.8 Product Cost and Price

The pin-on-disk testing apparatus has a production cost of $1350, and will be sold for $2000, leading to a profit margin of $650 per machine. Extra pins and disks are grouped into packs of five pins and one disk, which cost $25 per pack. They will be sold for $40 to give a profit of $15 each pack.

Figure 29 shows the cash flow for the pin-on-disk machines over two years from the beginning of the company. Assuming that production begins at the start of summer, the flow breaks even at the end of the following summer (month 15).

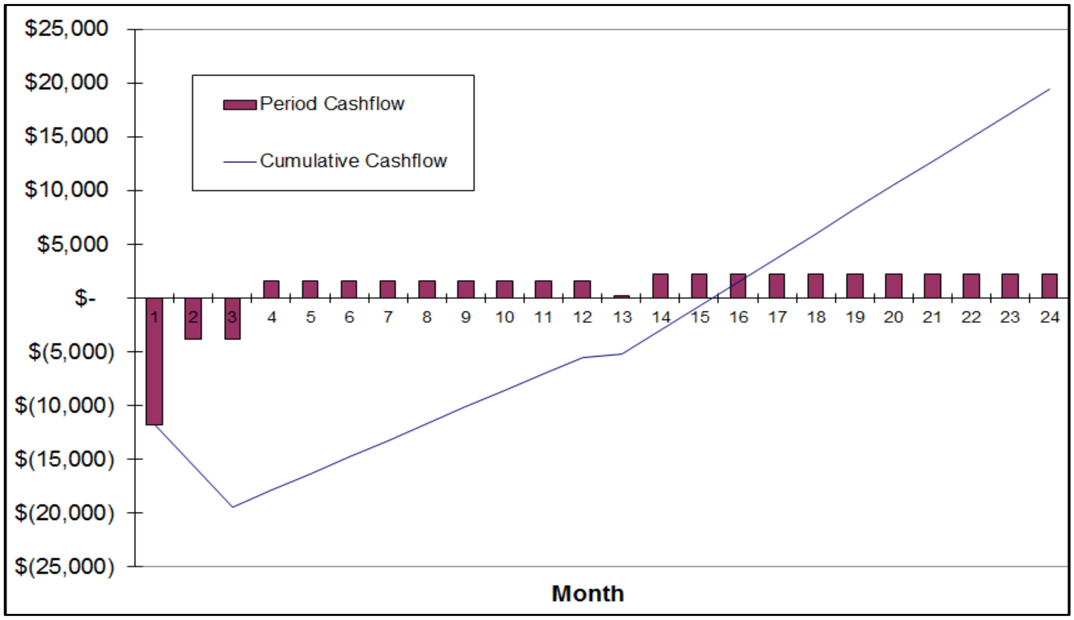

Figure 29 - Cash flow for pin-on-disk machine production and sales.

Figure 2 shows the cash flow for the supplementary pins and disks over the same two years. Even with the estimated sales dip over summer, profits remain high after breaking even in month 5.

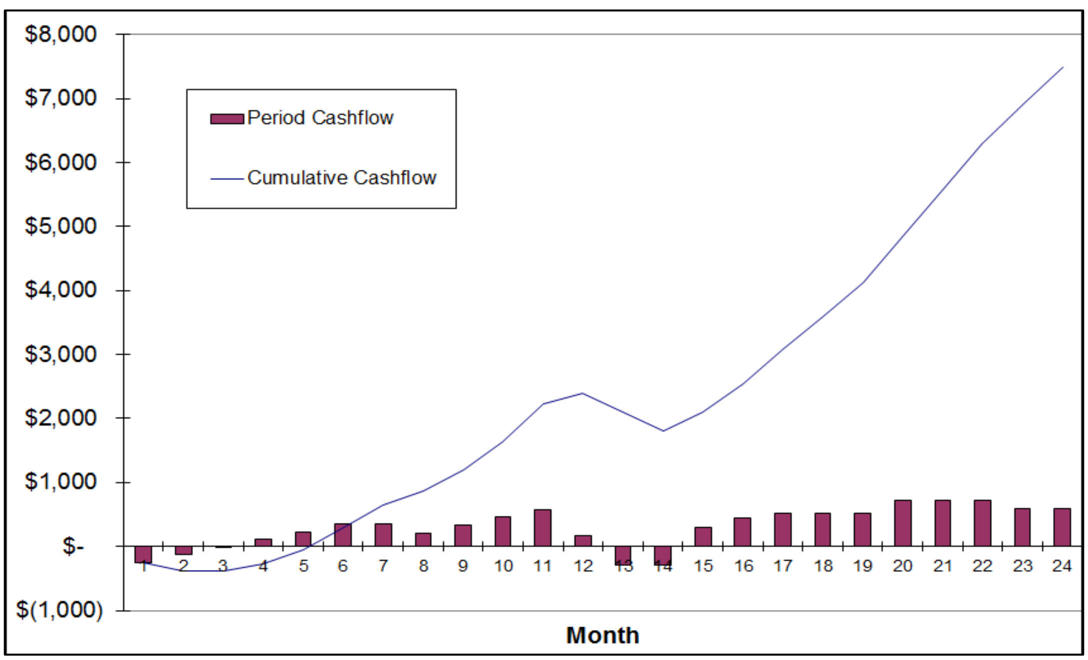

Figure 30 - Cash flow for extra supplies production and sales.

7.9 Services and Warranties

Even with a thorough instruction manual included, the company anticipates inevitable questions about the assembly process from customers. Users can reach out through email to ask for help with assembling and using the machines, preferably with pictures of its current state.

The product is expected to last for at least 2 school years with frequent use throughout semesters or quarters. If customer-provided images show one or more clearly damaged or missing parts, they can request replacement parts free of charge during that length of time after purchase. Customers can always purchase individual parts or sub-kits for slightly more than they would cost as part of the full kit.

7.10 Financial Plan and ROI

Table 12 outlines the financial estimates of Scholastic Instruments' two-year plan.

Table 12 - Estimated funding required, profits, and percent return on investment for SI

Value	Pin-on-disk machines only	Including extra pins + disks
Funding Required	$113,400	$127,900
Net Present Value	$18,193	$25,396
Return on Investment	125%	128%

SI will raise seed money from a variety of sources:

- Traditional small business loan
- National Science Foundation Small Business Innovation Research / Small Business Technology Transfer Program
- U.S. Department of Education's Small Business Innovation Research Program
- Venture Capital
    - Silicon Valley, and the wider Bay Area, has a large number of venture capital firms. Although SI is likely not to be as high-growth as other companies traditionally funded by venture capital, it may still be possible to find VC money in the area.

7.11 Contingency Plans

Scholastic Instruments is prepared for the inevitability that not everything goes perfectly. Table 13, on the next page, describes SI's plans for possible events that might interfere with the two-year plan.

Table 13 - Contingency plans for various roadblocks

Problem	Likelihood	Hazard Level	Mitigation
Vendor goes out of business/can't complete request	Medium	Medium	Always have at least two vendors that can provide each of the critical goods and services required to support the business.
Property protection in case of environmental emergency	Low	High	In data and equipment protection efforts, employees will use best judgment to decide if/when to abandon the efforts.
Fire	Low	High	Keep list of all materials that could cause/fuel fire, train employees in fire safety, have clear exit signage.
Unexpected large order	Medium	Low	Establish protocol with manufacturer; give appropriate lead times with cushion for possible backlog.
Customer wants to return apparatus	High	Medium	Money-back guarantee for 15 days providing customer has not damaged apparatus and it shows no visible sign of wear. Disks and pins are non-returnable.
Significant change in production cost	Medium	High	Always have at least two vendors that can provide each of the critical goods and services required to support the business. Adjust prices accordingly if necessary.
High-influence/profile customer expresses dissatisfaction with product publically	Medium	High	Direct contact with customer if possible, prepare media plan to mitigate damage to reputation.

8 Engineering Standards and Realistic Constraints

8.1 Social Impacts

8.1.1 Benefits of the Design Implementation

The design method behind the project will lead to several benefits:

1. Material research usable by future design teams
2. General treatment usable by other enterprises
3. Easier implementation compared to new technology

1. The project's early stages have produced data specific to AEST's augers that future teams helping the organization can use. This team will be the first to research and publish the auger's material properties, which are necessary for the best conceptual design. Other teams can use the published data instead of having to acquire and test their own samples. Wear and hardness data for this project's tested treatment ideas will also inform those teams' design strategy. AEST's future university partners will be able to help the enterprise much more efficiently using our research.

2. The goal of developing a process rather than a single auger means that other organizations can benefit as well. Instead of a physical item, the end product was a treatment prescription that anyone with the same resources and needs as AEST can perform on their own similar equipment. MIT's charcoal project leader reports that several social enterprises need the same kind of material improvement that AEST does. The end goal of a consistent, tested treatment will accommodate them with minimal extra work.

3. This project's nature as an improvement to existing machinery avoids problems that can come with introducing completely new technology. AEST and their extruders are well-established in Uganda, and the project will not add any new elements to their operation. Customers already enjoy the recycled briquettes and form a high-demand market for the project to contribute to [13]. This way the project can focus entirely on functionality without needing to factor in other marketing concerns. The well-defined need avoids the risk of designing a product that the target community rejects.

8.1.2 Potential Downside of Increased Charcoal

AEST's briquettes provide many benefits, as detailed in the next sections. However, these may encourage local Ugandans to continue using combustible fuel instead of switching to an entirely new energy source. Groups like the Uganda-focused Solar Energy for Africa (SEFA), as well as several current Santa Clara design teams, are developing solar solutions for households that lack reliable energy. The success of these projects partly relies on the large demand for energy that can heat and light these homes. Meeting this need through more of AEST's briquettes will diminish the energy demand in Teso, Soroti, and possibly beyond. Renewable energy projects will then need to provide a greater improvement in these regions to incentivize a change away from fossil fuel. The team believes that the benefits of helping AEST outweigh this downside of improving the auger.

8.2 Political

8.2.1 Gender Equality and Economics

Although present since Uganda gained independence in 1962, the modern Ugandan women's liberation movement finds its roots in the late 1980s after the end of the Luwero War. Since then, women have formed CSOs and NGOs to combat domestic violence, government corruption, and fight for equal rights [14]. Women have been at the forefront of fighting for the improvement of all Ugandan lives.

While Uganda's economy has grown in the last two decades, most of the growth has been in services such as banking and telecommunications, which employ less than 15% of the population. Over 70% of Ugandans work in agriculture, most as low-yield subsistence farmers. The economic growth enjoyed by other sectors has not reached them. Additionally, women in agriculture face problems that men do not, namely lack of access to credit, markets, tools, and transport. Women are traditionally allocated lower value subsistence crops while men farm cash crops. Women make up 70% of agricultural workers but their limited access to land prevents them from expanding past subsistence farming [14].

The sub-Saharan region has the highest share of female entrepreneurs in Africa, but many are self-employed and their enterprises are smaller and more informal than those of male entrepreneurs. It is thus not a matter of helping more women become entrepreneurs, but transitioning the existing ventures to higher economic-return activities. While the number of female entrepreneurs is high, many women are stuck working in the home. With much of their time spent doing housework and caring for family members, they are unable to earn a wage [14].

8.2.2 Impact on Appropriate Energy Savings Technology Limited

Appropriate Energy Savings Technology Limited is a division of the Teso Women Development Initiative (TEWDI), also founded by Betty Ikalany. Their mission statement is "[b]ringing Health, Education and Safety to Women and Children in Uganda;" however, not all of their employees are women. This fact can be seen in photographs on the project's website, which show both men and women with the augers and extruder machine. However, the previous researchers assumed that all employees were female [2]. While seemingly a small oversight, it is an important reminder to not make assumptions, especially when working with people from other countries and cultures. As reported by Lindsey Wang, women mostly worked in management positions, while men were the ones who actually operated and repaired the extruder machines. Non-managerial female employees worked cooking the cassava porridge used as a binder for the briquette mixture.

It was also reported that Betty Ikalany expressed interest in having another female employee, Eva, work with the MIT students on case hardening. Eva was a cook both in her own home and for TEWDI, and her experience with stoves and fires would help with the case hardening process. While Eva offered several key insights that helped with the construction of the oven for the auger, her cooking duties took up most of her time and prevented significant involvement [2]. Although Eva was objectively the most qualified to help with the furnace construction, her duties as cook prevented her from taking on a large role in the project. Although it is unwise to simplify this situation to only the effects of gender roles, these traditional patterns cannot be ignored.

8.2.3 Supporting AEST's Mission

There are small ways to support AEST's mission of uplifting women and girls in Uganda with the Extrusion Auger Improvement Project. As it is unlikely that the team will be able to travel to Uganda, a manual will be made to cover the improved hardening or coating process. In the manual both male and female figures will be depicted working with the augers and implementing the improvements. Normalizing women working in technical positions or working with machinery is something that needs to be done worldwide, and will help facilitate growth of female-held capital.

8.3 Health and Safety

Although Materials Science is often considered part of Mechanical Engineering, the discipline has its own organizations. Possible organizations and standards that will need to be consulted are:

- ASTM International (American Society for Testing and Materials)
- American Society of Mechanical Engineers
- ASM International (American Society for Metals)
- National Institute of Standards and Technology

At present, ASTM has been the most relevant body. ASTM Active Standard G99-05 "Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus" has been consulted in the design of the pin-on-disk testing apparatus [7]. Although the apparatus constructed will not be sold, it is helpful to use the standard as a guideline.

8.3.1 Process Safety

The current method of case hardening designed by the MIT D-Labs team is not safe. In videos sent to the current team, MIT students and AEST employees tried to pick up the augers from the kiln using a combination of metal rods and sticks. They wore no protective gear other than thick gloves, and there is a real danger of sparks, or even the hot auger, touching skin. At one point, the auger comes in contact with the dirt outside the kiln and ignites some dry grass [15]. A screenshot of this video can be seen in Figure 9 on the next page.

Figure 31 - The auger is removed from the kiln using sticks and metal rods, reproduced with permission [15].

8.3.2 User Health

Designing a successful auger will also improve health for Ugandans who buy AEST's briquettes. More briquettes mean more households in Teso and Soroti with access to cleaner charcoal. Wood-based charcoal produces very harmful smoke, which is the main factor in 13,000 Ugandans' deaths annually by AEST's estimate [1] The recycled briquettes burn longer and produce much less smoke compared to wood charcoal [13]. Aiding them with an enhanced auger will let more families avoid health-threatening wood charcoal.

With AEST's briquettes, families can also save time used to gather other fuel sources. Since fire is too important for homes without electricity to forgo despite the health risks of wood smoke, many families must chop their own firewood. According to AEST, 95% of the population depends on firewood in some way [1]. This time-consuming task often falls to women. AEST's recycled briquettes allow women to go to school and work instead [1]. A better auger means more fuel available to give families this opportunity.

8.4 Environmental Impact

8.4.1 Reduced Emissions

Charcoal briquettes made from agricultural waste are part of the solution to providing cleaner energy in Uganda. In a user study of 23 households performed by the MIT D-Labs in Uganda, 22 households using the ag-waste charcoal briquettes reported that there was less smoke produced than when they used wood charcoal. [13]. Additionally, 22 households reported that the ag-waste briquettes produced more heat than wood briquettes and 19 households reported that it took less ag-waste charcoal to perform the same tasks than with wood charcoal [13].

8.4.2 Reduced Deforestation

The recycled briquettes also keep Ugandans from needing to cut trees for fuel, helping to curb the serious deforestation the country is facing. The forested percentage of Uganda's total land is now less than half of its 1990 value, dropping from 23.78% to 10.36% in 25 years [16]. This is a major motivation behind AEST's briquette program [1]. Letting AEST recycle more briquettes will slow down the deforestation by giving families an alternative fuel.

8.5 Sustainability

8.5.1 Current Process

The current auger improvement process used by AEST is not sustainable. Case hardening must be performed after an average of three work days consisting of six hours each. This constant process of auger improvement is not ideal, and prevents AEST from reaching its full capacity. On average, AEST produces one half ton of charcoal per day between the three extruder machines; however, if all machines were continuously used, this could increase to three-fourths of a ton per day. Although quantitative data has not been taken, there is only a finite number of times an auger can be case hardened before it loses structural integrity. Eventually, a new auger must be commissioned and the cycle repeats.

Although the previous researchers expressed satisfaction with their results, it is clear that Betty Ikalany desires more improvement. Most of the evidence of MIT's improvements is anecdotal. Lindsey Wang asked for follow-up measurements of the screw diameter and flight thickness after she left Soroti but never received this data. In a write-up Wang completed after her visit, she noted:

> "[Betty] reported that the control screw had worn out after producing 6-tons of charcoal briquettes while the case hardened screw continued to be function properly [sic] long after it passed the 6-ton marker. This suggests that the case hardening procedure successfully increased the lifespan of the extruder screw without sacrificing the quality of the produced briquettes." [2]

8.5.2 Provenance of Materials

The previous researchers also placed significant importance on using locally available material. In the team's interview with her, Betty Ikalany explained that importing augers would be a last resort, but she was willing to consider it in order to meet her production goals. She aims to drastically increase production to one ton per hour. For this reason, our project also considered metals and materials not readily available in rural Soroti. However, the benefits of these metals were outweighed by their increased costs and they were not good options.

9 Summary and Conclusions

9.1 Lessons Learned

In the design phase, the main lesson learned was how to build an apparatus while still designing it. Many of the body parts were fabricated before the motor was bought, and had to be made to accommodate motors of different sizes. Calculations can help in the design phase, but sometimes there is no satisfactory equation that encompasses all facets of the situation. Finally, don't leave the question of how to actually fabricate the concept for a later date. A good idea is worthless if it cannot be actually be fabricated with the available tools.

In the fabrication phase, the main lesson learned was that it was nearly impossible to estimate the amount of time machining a certain part would take. While an experienced machinist could likely make these estimations with ease, as new machinists the team struggled with this aspect of managing fabrication. Similarly, many designs had to be tweaked for feasibility, and changes to the accompanying documentation should be made as soon as possible. Double-checking even simple measurements goes a long way to prevent mistakes and miscommunication.

In the testing and analysis phase, the main lesson learned was that with a custom apparatus and testing system, there are going to be early trials that cannot be used in the final results. Having enough specimens fabricated so that the first 3 tests could be used to verify the machine and methods were working properly was key to the success of later trials. Although it is disheartening, sometimes trials must be scratched due to human error and re-done.

9.2 Future Improvements

The pin-on-disk apparatus could be improved by adding a revolution counter or time counter that would shut off the machine after a certain point. Although manually stopping the apparatus after each test was not a large inconvenience, the apparatus was noisy and disturbed other students working in the materials lab. The ability to run the machine overnight and have it stop automatically would be a worthwhile improvement as it would increase the number of tests that could be run per day from 2 to 3. The machine was able to be carried by one person, however it was a little unwieldy and could be improved by cutting down the wood base and re-machining the steel vertical arms in a lighter metal such as aluminum. The charcoal cup worked well, but could be improved by making the walls higher so that the apparatus.

Future teams would be well served by being able to visit AEST in Uganda and take in-field measurements. In particular, the rotation speed of the auger inside the extruder and the temperature that the inside of the extruder reaches are important environmental factors that are currently unknown. This project did not explore changing the shape of the auger, but likely improvements can be made there.

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Appendix A: Project Timeline and Budget

Table A 1 describes the expenses the project was expected to require, while Table A 2 tallies the grants that have provided income for the project.

Table A 1 – Projected Project Expenses

Category	Item	Est. Expense
Supplies	Pin-on-disk construction materials	-$1500
	Consumable post-treatment testing supplies	-$1500
	Original auger for testing and examination	-$500
Travel	Transport to present in engineering conference at project end	-$1000 X 2
Contracted Services	Contractor for material coating application	-$500
Total		**-$6000**

Table A 2 – Project Income

Category	Source	Income
Grants	Roelandts Grant in Sci and Tech for Social Benefit	+$4000
	SCU School of Engineering	+$1000
Total		**+$5000**

Table A 3 - Expenditures

Category	Component Description	# Of Items	Vendor	Cost/Part	Cost
Apparatus					
Motor	Used Buehler Motor	1	EBay 1623blair	$75.00	$75.00
	Motor + Driver	1	Oriental Motors	$451.35	$451.35
	Bracket	1	Oriental Motors	$29.00	$29.00
	Wall Cable	1	Oriental Motors	$18.00	$18.00
	Stainless Steel Disk	3	Parametric (Santa Clara)	$59.42	$178.25
	Plastic Charcoal Cup	1	3D Print On Campus	$20.00	$20.00
	Supporting Plate	1	EBay	$30.00	$30.00
	Test Disk	1	EBay	$12.25	$12.25
	Plate Plug	1	From Machine Shop	$0.00	$0.00
	Interface Shaft	1	From Motor	$0.00	$0.00
Pin Holder	1.5" Alum Pin-Holding Pipe	1	Online Metals	$6.94	$6.94
	Pipe Strap/Strong-Tie	1	Simpson/Home Depot	$2.97	$2.97
	0.5" Screw	1	Home Depot	$4.24	$4.24
	.75" Screw 8-Pack	2	Home Depot	$1.18	$2.36
Frame	Vertical Arm Support	2	Online Metals	$9.02	$18.04
	Horizontal Arm	1	Online Metals	$18.79	$18.79
	Feet	1	Online Metals	$11.96	$11.96
	Connecting Pin	1	Everbilt/Home Depot	$1.97	$1.97
	Hex Nut	2	Everbilt/Home Depot	$0.22	$0.44
	Washer	2	Everbilt/Home Depot	$0.22	$0.44
	Sheet Metal Frame Piece	2	Online Metals	$9.79	$19.58
	8-Count #8 X 1.25-In Round-Head Zinc-Plated Slotted-Drive Interior/Exterior Wood Screws	1	Lowes	$1.24	$1.24
	14-Count #8 X 0.5-In Flat-Head Zinc-	2	Lowes	$1.24	$2.48

	Plated Interior/Exterior Wood Screws				
	6-Count #8 X 2-In Round-Head Zinc-Plated Slotted-Drive Interior/Exterior Wood Screws	1	Lowes	$1.24	$1.24
	8-Count #8 X 1.5-In Flat-Head Zinc-Plated Interior/Exterior Wood Screws	1	Lowes	$1.24	$1.24
	6" PVC Pipe SCH 40, Charlotte Pipe $1.69 By The Inch, CHARLOTTE PIPE SCH 40.	1	EBay	$11.15	$11.15
	Everbilt 1 In. Steel Zinc-Plated Corner Brace (4-Pack)	1	Home Depot	$2.38	$2.38
	Everbilt #6 X 1/2 In. Philips Zinc-Plated Flat-Head	1	Home Depot	$1.18	$1.18
	Gardner Bender 16 - 14 AWG, #8 - 10 Stud Size Blue Ring	1	Home Depot	$2.18	$2.18
	3/4" Plywood	1	Lowes	$16.47	$16.47
	2"X4" Stud	1	Lowes	$2.72	$2.72
				Total	**$943.86**
Misc.	**Component Description**	**# Of Items**	**Vendor**	**Cost/Part**	**Cost**
	Crucibles	3	Advalue Tech	$26.40	$79.20
	Crucible Lids	2	Advalue Tech	$20.06	$40.12
	Crucibles	2	Advalue Tech	$25.03	$50.06
	Crucible Lids	2	Advalue Tech	$24.00	$48.00
	Stainless Steel Pins	1	Amazon	$6.74	$6.74
	Graphite	1	EBay	$11.99	$11.99
	Alum Bar 0.5 X 0.5	1	Online Metals	$10.17	$10.17
	Tongs	1	San Jose Scientific	$8.67	$8.67
	Latex Gloves	1	Home Depot	1.98	1.98
	Disposable Masks	1	Home Depot	$5.47	$5.47
	Blue Scotch Tape	1	Home Depot	$6.91	$6.91
	Black Rust-Resistant Paint	1	Home Depot	$3.96	$3.96
	Welding Gloves	1	Home Depot	$14.98	$14.98
	Lump Charcoal	1	Home Depot	$9.97	$9.97

	Paint Brush	1	Home Depot	$3.11	$3.11
	Mineral Oil	4	Target	$2.32	$9.28
	Testing Supplies (Sepehrband)	1	--		$900
				Total	**$1,210.61**
Material Specimens	**Component Description**	**# Of Items**	**Vendor**	**Cost/Part**	**Cost**
	Pin Material 1 (1018 Steel)	4	Online Metals	$2.22	$8.88
	Pin Material 2 (1045 Steel)	1	Online Metals	$5.35	$5.35
	Pin Material 3 (12L14 Steel)	1	Online Metals	$0.94	$0.94
	Pin Material 4 (8620 Steel)	1	Online Metals	$1.92	$1.92
	Disks	3	Parametric	$178	$178
				Total	**$195.09**
Additional Large Purchase	**Component Description**	**# Of Items**	**Vendor**	**Cost/Part**	**Cost**
	LW Measurements Analytical Balance	1	LabPro Sunnyvale	$1,400	$1,400
Totals		**$3,750**			

Table A 4 - Detailed Timeline, December 2016 to June 2017

Deliverable	Dec. ’16	Jan. ‘17	Feb. ‘17	Mar. ‘17	Apr. ‘17	May ‘17	Jun. ‘17
Design Testing Equipment	■						
Order Materials to Build Testing Equipment	■						
Fabricate Pin-on-Disk Apparatus		■					
Test Pin-on-Disk Quality		■					
Locate Manufacturer for Stainless Steel Disk	■						
Order Stainless Steel Disks		■	■				
Order Material for Pins to Treat		■					
Test Auger Specimens		■					
Design Treatments, Coatings			■	■	■		
Send Pin Samples to Off-Site Lab for Coating			■	■	■		
Heat-Treat Pins			■	■	■		
Test Treated Pins in Pin-on-Disk				■	■		
Analysis and Microscopy				■	■	■	
Cost Analysis of Pin Treatments					■	■	
Final Suggestion						■	
Senior Design Conference						■	
Thesis						■	■

Appendix B: Selection Matrices

Table B 1 - Selection matrix for overall pin-on-disk frame

CRITERIA	FACTOR	Baseline		Rotating disk		Revolving pin		Double supports	
Weight	1	3	3	3	3	3	3	4	4
Portable Size	1	3	3	3	3	3	3	5	5
Pin Straightness	5	3	15	3	15	2	10	4	20
Vibration Damping	5	3	15	5	25	1	5	3	15
Max Operation Time	3	3	9	4	12	3	9	3	9
Easy Height Adjustment	2	3	6	3	6	3	6	5	10
Charcoal Applicability	5	3	15	1	5	5	25	4	20
	TOTAL		66.0		65.7		54.3		63.0
	RANK		1		2		4		3
	% MAX		100.0%		99.5%		82.3%		95.5%

Table B 2 - Selection matrix for loading mechanisms

CRITERIA	FACTOR	Baseline		Pulleys		Weights on top		Spring		Lead screw	
Effective Load Transmission	4	3	12	3	12	4	16	2	8	2	8
Vertical Load Transmission	5	3	15	3	15	5	25	1	5	4	20
Precisely Adjustable Load	3	3	9	2	6	2	6	5	15	5	15
Low Complexity	2	3	6	2	4	5	10	3	6	3	6
Easily Measured Load	3	3	9	4	12	4	12	1	3	1	3
Added Height Adjustment	1	3	3	3	3	1	1	5	5	5	5
	TOTAL		54.0		72.0		90.0		62.0		77.0
	RANK		5		3		1		4		2
	% MAX		60.0%		80.0%		100.0%		68.9%		85.6%

Table B 3 - Selection matrix for charcoal application

CRITERIA	FAC-TOR	1 = Baseline		Hour-glass trickle		Interval deposits		Per revo-lution		Pin follower		Tube around Pin		Charcoal Cup	
Coating Consistency	2	3	6	3	6	3	6	3	6	5	10	5	10	5	10
Charcoal Capacity	1	3	3	5	5	3	3	3	3	3	3	2	2	4	4
Reliable Delivery	4	3	12	4	16	2	8	2	8	5	20	5	20	5	20
Long-term Operation	4	3	12	5	20	2	8	2	8	2	8	4	16	5	20
High-rpm Operation	2	3	6	4	8	3	6	3	6	3	6	5	10	3	6
User-Friendliness	3	3	9	5	15	3	9	3	9	3	9	3	9	4	12
Ease Of Manufacture	2	3	6	5	10	4	8	3	6	1	2	1	2	5	10
Ruggedness	3	3	9	4	12	5	15	3	9	3	9	5	15	5	15
	Total		63.0		108.7		76.3		68.3		73.7		104.0		117.0
	RANK		7		2		4		6		5		3		1
	% MAX		53.8%		92.9%		65.2%		58.4%		63.0%		88.9%		100.0%

Appendix C: Additional Subsystem Data

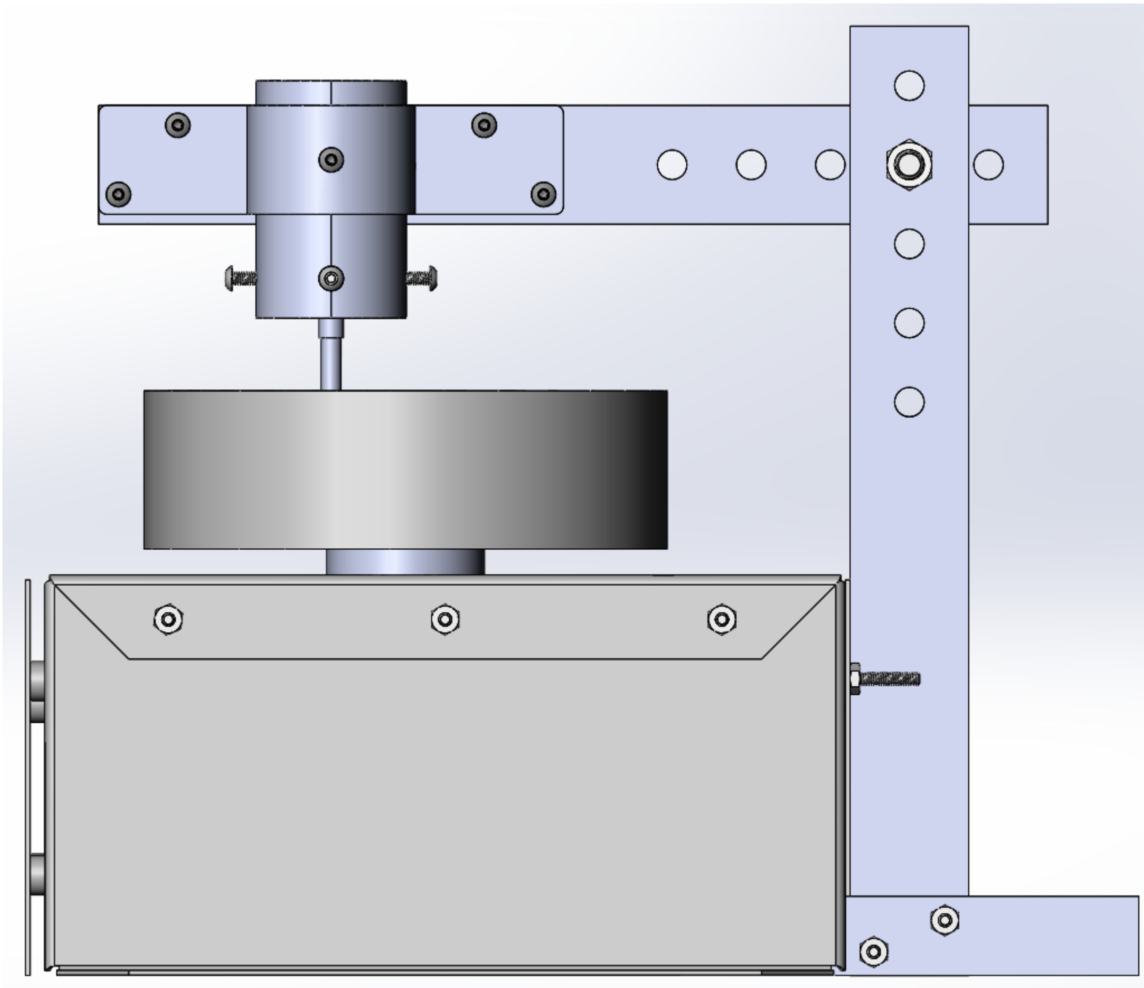


Figure C 1 - Additional View of Pin-on-Disk Assembly CAD.

ORIENTAL MOTOR U.S.A. Corp.
1001 Knox Street
Torrance, CA 90502
1-800-GO-VEXTA (468-3982)

All Categories > Item # BMU230A-5-3

Item # BMU230A-5-3, Brushless DC Motor Speed Control System

The BMU Series features a compact, high-power and high-efficiency brushless DC motor (BLDC motor) and is combined with an easy to use, easy to set speed controller. The entire motor structure features our latest brushless DC motor technology and has been innovated in pursuit of the optimal performance.

- High-efficiency motor
- Wide Speed Control Range
- Easy wiring and set up
- Expanded functions

*Includes 9.8 ft. (3 m) connection cable.

Lead Time | Specifications | Speed Control Features

Lead Time

Specifications

Motor Type	Brushless DC Motor
Motor Frame Size	2.36 in.
Output Power	30 W (1/25 HP)
Power Supply	Single-Phase 100-120 VAC
Shaft/Gear Type	Parallel Shaft Gearhead
Gear Ratio (X:1)	5 :1
Output Shaft Diameter	10 mm
Rated Torque	3.90 lb-in
Electromagnetic Brake	Not Equipped
Variable Speed Range (r/min)	16 ~ 800

Figure C 2 – Page 1 of motor specifications.

Permissible Load Inertia	66 oz-in²
Permissible Overhung Load	0.39 in. from Shaft End = 22 0.79 in. from Shaft End = 33 lb
Permissible Axial Load	9 lb
Max. Extension Length (m)	10.50
Components	BLM230-52 [Gearmotor] = {BLM230-GFV2 [Motor] / GFV2G5 [Gearhead]} BMUD30-A2 [Driver] See Downloads for January 2015 Design Change details.
RoHS Compliant	These products do not contain substances that exceed the regulation values in the RoHS Directive.
Safety Standards	UL CSA CE
CE Marking	Low Voltage Directives EMC Directives
Insulation Resistance (Motor)	100 M Ω or more when 500 VDC megger is applied between the windings and the case after continuous operation under normal ambient temperature and humidity.
Insulation Resistance (Driver)	100 M Ωor more when a 500 VDC megger is applied between the power supply terminal and the protective earth terminal and between the power supply terminal and the I/O signal terminal after continuous operation under normal ambient temperature and humidity.
Dielectric Strength (Motor)	Sufficient to withstand 1.5 kVAC at 50 Hz applied between the windings and the case for 1 minute after continuous operation under normal ambient temperature and humidity.
Dielectric Strength (Driver)	No abnormality is judged even with application of 1.5 VAC at 50 Hz between the power supply terminal and the protective earth terminal and with application of 1.5 kVAC at 50 Hz between the power supply terminal and the I/O terminal for 1 minute after continuous operation under normal ambient temperature and humidity.
Temperature Rise (Motor)	The maximum temperature rise of the windings is 90°F (50°C) and that of the case is 72°F (40°C) when measured by the thermocouple method after rated continuous operation under normal ambient temperature and humidity.
Temperature Rise (Driver)	Temperature rise of the heat sink is 90°F (50°C) or less measured by the thermocouple method after rated continuous operation under normal ambient temperature and humidity.
Ambient Temperature Range	32°F ~ 104°F (0°C ~ 40°C), nonfreezing
Ambient Humidity	85% or less, noncondensing
Altitude	Up to 3300 ft (1000 m) above sea level.
Operating Atmosphere	No corrosive gases or dust. Cannot be used in a radioactive area, magnetic field, vacuum or other special environment.

Figure C 3 - Page 2 of motor specifications.

Thermal Class	CSA standards: 105 (A), EN standards: 120 (E) UL
Degree of Protection	Motor [IP40] [Driver] IP20

Speed Control Features

Speed Control Method (Select one of the following)	Digital Setting using the dial
Number of Speed Settings	4
Acceleration/Deceleration Time	Analog Setting: 0.1 ~ 15.0 s (Time setting from stopped state until reaching rated speed) Common setting for acceleration/deceleration time with the use of acceleration/deceleration time potentiometer*. Digital setting: 0.0 ~ 15.0 s (Time setting from current speed to setting speed) Individual settings for acceleration time/deceleration time for each operating data*. *Acceleration time/deceleration time varies with the load condition of the motor.
Input Signals	Photocoupler Input method Input Resistance: 5.7 kΩ Operation by internal power supply: 5 VDC Connectable External DC Power Supply: 24 VDC -15~+20% Current 100 mA or more Sink input/Source input Supplied through external wiring. Arbitrary signal assignment to X0~X2 input (3 points) is possible [ ]: Initial Setting [FWD], [REV], [MO], ALARM-RESET, EXT-ERROR, H-FREE.
Output Signals	Photocoupler and Open-Collector Output External Power Supply: 4.5 ~ 30 VDC Current 100 mA or less Sink output/Source output Supplied through external wiring. Arbitrary signal assignment to Y0, Y1 (2 points) is possible [ ]:Initial Setting [ALARM-OUT1], [SPEED-OUT], ALARM-OUT2, MOVE, VA, WNG
Protective Function	When the following protective functions are activated, ALARM-OUT1 output turns OFF and the motor will undergo a coasting stop. At the same time, the alarm code will be displayed. (Instantaneous stop for external stop only) Overcurrent, Main circuit overheating, Overvoltage, Undervoltage, Sensor error, Overload, Overspeed, EEPROM error, Initial sensor error, Initial operation inhibition, External stop
Time Rating	Continuous

[1] Quoted Ship Date for orders placed before 12:00 pm PST. Quantities may affect Shipping Date.

Figure C 4 - Page 3 of motor specifications.

Connection and Operation [30 W (1/25 HP), 60 W (1/12 HP), 120 W (1/6 HP)]

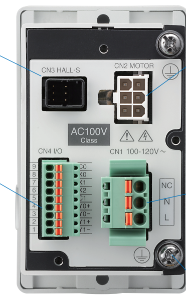
●Names and Functions of Driver Parts

Displays the monitor contents, alarm, etc.

Changes the speed and parameters.
The value is set when the dial is pressed after changes are made.

The motor is started by setting it to the "RUN" position.
Setting it to the "STAND-BY" position stops the motor.

Changes the rotation direction of the motor.



Connects to the motor sensor connector (black).

Connects with the I/O signals.

Connects to the motor's motor connector (white).

Connects to the main power supply.

Ground either one of the protective earth terminals.

◇When Front Panel is Removed

Changes the operating mode.

Changes the indication and functions for the operating mode.

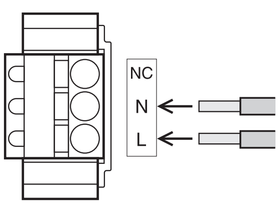
Sets the acceleration time for starting the motor and deceleration time for motor standstill.
Setting Range: 0.1 s~15.0 s

●Extended Functions

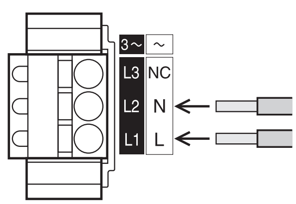
Operating Mode	Details
Monitoring	Speed, load factor, operating data number, alarm code, warning, I/O monitor
Data	4 data points Speed, acceleration time, deceleration time, reset
Parameters	Gear ratio, speed increasing ratio, initial panel display, initial operation prohibition alarm, initial operation prohibition alarm cancellation method selection, analog acceleration/deceleration, speed upper limit/lower limit setting function, simple holding selection, external operating signal input, input function selection, output function selection, overload alarm detection time except when shaft is locked, overload warning label, speed attainment band, parameter mode reset

◇Main Power Connector (CN1)

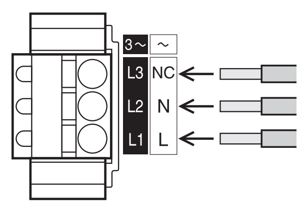
●Single-Phase 100-120 VAC



●Single-Phase 200-240 VAC



●Three-Phase 200-240 VAC



●Applicable Lead Wire Size

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●Operation with the Driver Only

◇Run/Stop

◇Speed Setting Method

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●Operating Switch

Figure C 5 – Page 1 of motor connection and operation guide.

Operation by External Signals

◇Operating Method

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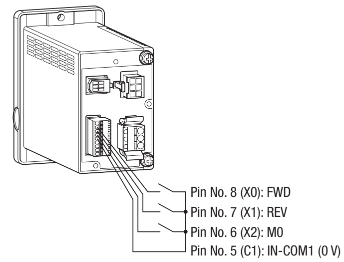

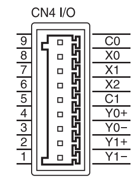

•I/O Signal Connector (CN4)

Pin No.	Terminal Name	Function*	Description
9	C0	IN-COM0	Input Signal Common (External power supply)
8	X0	[FWD]	The motor rotates in the forward direction when "ON."
7	X1	[REV]	The motor rotates in the reverse direction when "ON."
6	X2	[M0]	Selects the operating data.
5	C1	IN-COM1	Input Signal Common (Internal power supply: 0 V)
4	Y0+	[SPEED-OUT]	30 pulses are output when the motor output shaft makes one rotation.
3	Y0−		
2	Y1+	[ALARM-OUT1]	Turns OFF when an alarm is activated. (Normally closed)
1	Y1−		

*The text inside the [ ] represents the factory default function assignment.
The following signals can be assigned as necessary to 3 input signal terminals (X0～X2) and 2 output signal terminals (Y0, Y1).
3 of the 7 input signals (FWD, REV, M0, M1, ALARM-RESET, EXT-ERROR, H-FREE)
2 of the 6 output signals (ALARM-OUT1, SPEED-OUT, ALARM-OUT2, MOVE, VA, WNG)

•Applicable Lead Wire Size

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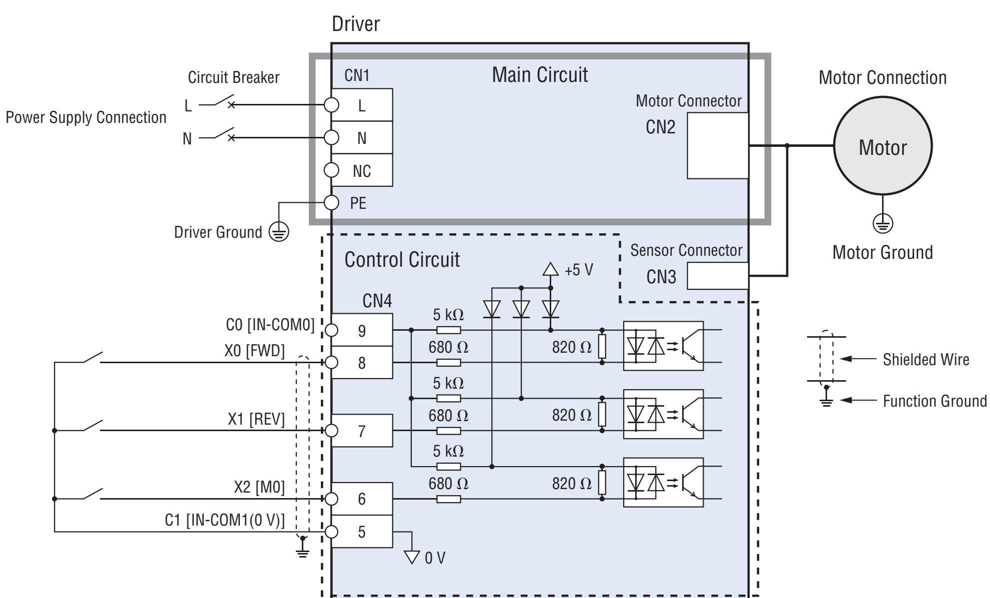
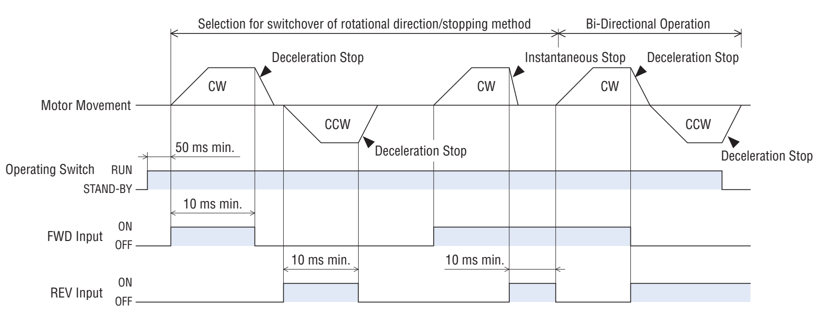
◇Connection Example Using Switches and Relays



◇Timing Chart



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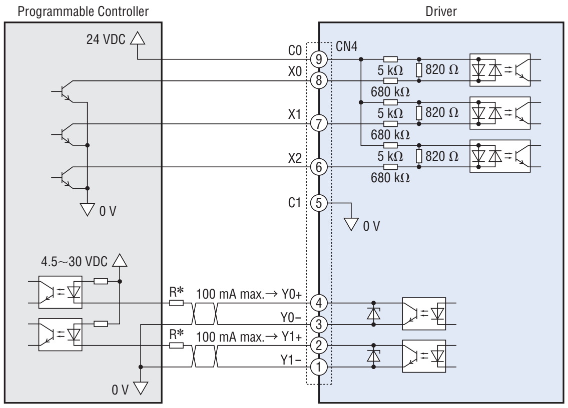
●With the combination type, the rotation direction varies according to the gear ratio of the gearhead.

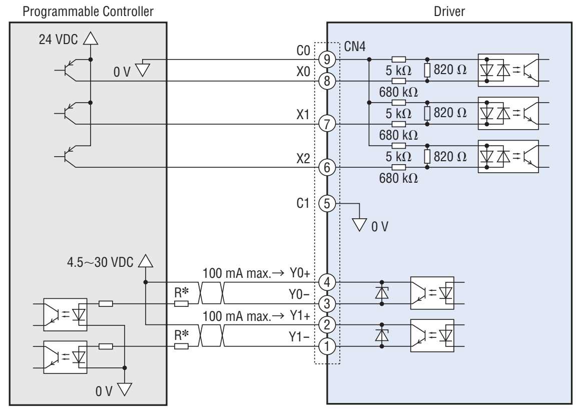
Figure C 6 - Page 2 of motor connection and operation guide.

◇I/O Signal and Programmable Controller Connection Examples

● Sink Logic



● Source Logic

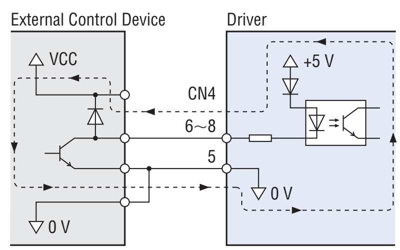


✻Recommended Resistance Value
24 VDC: 680 Ω~2.7 kΩ (2 W)
5 VDC: 150 Ω~560 Ω (0.5 W)

Note

Maintain the current value of Y0 and Y1 at 100 mA or less. If this current value is exceeded, connect the limiting resistor R.

◇When an External Control Device with a Built-In Clamp Diode is Used



◇When Multistep Speed-Change Operation is Used

● Operating Condition Example

Operating Data No.	M0	M1	Speed [r/min]
0	OFF	OFF	3000
1	ON	OFF	1000
2	OFF	ON	2000
3	ON	ON	500

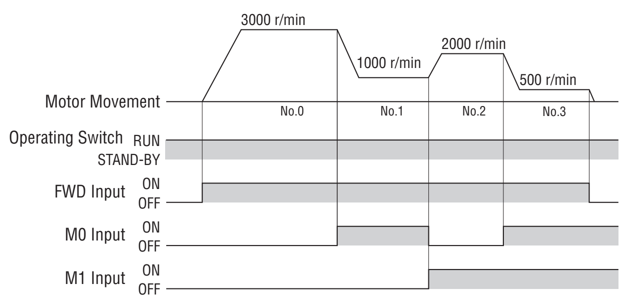


Figure C 7 - Page 3 of motor connection and operation guide.

Appendix D: Problem Design Specification

Table D 1 shows the PDS for the pin-on-disk apparatus, based on the custom pin-on-disk machine created for an experiment by two Egyptian scientists [17].

Table D 1 - PDS for pin-on-disk machine

Elements		**Parameters**	
Requirements	**Units**	**Datum**	**Target Range**
Dimensions			
Overall Height x Width x Depth	cm^3	unknown	Max: 30 x 30 x 30
Pin Diameter	mm	8	N/A, depends on sample received
Pin Height	mm	15	N/A, depends on sample received
Disk Diameter	mm	95	150 - 180
Disk Height	mm	20	6-10
Track Radius	mm	27	60-80
Motor Shaft Diameter	mm	13	Calculated from motor
Total Weight	kg	unknown	< 4.5
Operation			
Pin or Disk Rotation Speed	rpm	1400	< 1000
Normal Load	N	9.8 - 29.4	10-40
Operating Time	min	2 - 4	> 120

Appendix E: Interviews

Skype Interview October 13, 2016

Interviewers: Maureen O'Neill, Aaron Wagner
Student Members of Extrusion Auger Project
Interviewee: Betty Ikalany
CEO of Appropriate Energy Savings Technologies
Based in Soroti, Uganda
Client for Improved Extrusion Auger

Who did you work with before?
Worked with the MIT D-Labs, they have worked on strengthened by "burning and cooling the augers with water"
What metal are you currently?
Unknown, possibly mild steel
Can you send us small pieces of the auger or the charcoal mix?
Maybe? Will send us the report from MIT
Where are the augers manufactured?
The Augers are made locally in Uganda. They were designed in partnership with the MIT D-Labs and are produced by Central Engineering Co.
What are some of your desires for the project in general?
Improve life of the auger
Mild steel coating? (needs confirmation from MIT)
Increase market served
Really want the briquettes to be of a uniform shape and length, want some sort of automatic cutting implement
What is your current briquette output?
Current: ½ tons in a 6 hour work day
Desired: 1 ton per hour, 5 hours a day
3 work days per week
Worried that this increase production will increase wear
Currently there are 4 extrusion machines, but they can't all be used at the same time as the augers wear out so quickly
What is typical wear on the auger?
An auger that has not been hardened will only last about 1 work day (6 hours)
After hardening, lifespan is about 3 days (18 hours)
What is the rest of the machine made out of?
Unknown, must acquire information from MIT-D Labs

In-person Interview October 28, 2016

Interviewers: Maureen O'Neill, Aaron Wagner
Student Members of Extrusion Auger Project
Interviewee: Panthea Sepehrband
Professor of Mechanical Engineering, Santa Clara University
Principal Investigator, Extrusion Auger Improvement Project

What seems like a feasible amount of auger lifetime? (we estimate 30 hours, up from 18)

Guess - maybe MIT has already made it good, but coating may still improve

What seems like a feasible level of briquette production? (Ikalany's goal is 1 ton/hr for 5 hrs, up from 0.5 tons every 6 hrs)

Speed up rotation, which increases wear; so resisting wear will increase briquette production

Also Ikalany said they could start using all machines at the same time

Again, need a bit more info for specifics

How important will surrounding temperature/heat through friction be in choosing material?

Very important because of heat treatment: steel has many forms, and martensite will be made by quenching in water, which they do; if the extruder gets too hot, it will temper the martensite into a weaker material; this may be why they have to keep rehardening

How commonly available are materials we might use for coating? (Goal is to make a process they can do in Uganda)

Not sure - perhaps why coating is not yet there; we can recommend levels of what would work best vs. what to do if those are unavailable.

Surface hardening is another option; in steel, increases carbon levels on outside for hardness, keeps inside ductile

How much could a material change/outer coating affect the machine's mechanical function? (i.e., even a slight dimensional change important?)

Nope, should be fine, since if they keep using the same auger it must not be that precise

In-person Interview November 2, 2016

Interviewers: Maureen O'Neill
Student Member of Extrusion Auger Project
Interviewee: Robert Marks
Professor of Mechanical Engineering, Santa Clara University

What seems like a feasible amount of auger lifetime? (we estimate 30 hours, up from 18)
- This seems like a reasonable amount of stuff for a senior design, but why did you choose 30 hours
- Notes: 30 hours was chosen because it was a full work week, and that way one person could come and change it out at the beginning of the week and it would last until the next week

What seems like a feasible level of briquette production? (Ikalany's goal is 1 ton/hr for 5 hrs, up from 0.5 tons every 6 hrs using not all available machines)
- Unknown

How important will surrounding temperature/heat through friction be in choosing material?
- If you're looking at coating (oxide, carbide, nitride) friction is not much of an issue
- Our temperature does not even reach 200 C, so most coatings would be fine at temperatures much above this from a chemical stability standpoint

Would be more of an issue with a paint or plastic which would possibly not work as well at higher temperatures
- Nitriding the surface of steel: thermal expansion (thermal misfit) and then contracting could cause coating to flake off

How commonly available are materials we might use for coating? Charcoal mix
- Most obvious: carbon or nitrogen treating the surface
- Aluminum oxide: if it was an aluminum based part

How much could a material change/outer coating affect the machine's mechanical function? (i.e., even a slight dimensional change important?)
- What do they want the tolerance between the outer tube and the auger to be?
- This could be what is causing them to not work
- Doesn't see it as a big issue
- A wild idea: the iron-chrome diagram, there is quite a bit of solubility there
- Alloy of iron with chrome, get it an oxidizing heat treatment to get chromium oxide

Email Interview, concluded November 2, 2016

Interviewers: Aaron Wagner
Student Member of Extrusion Auger Project
Interviewee: Lindsey Wang
MIT D-Labs Auger Project Student Member

Question Summary:

Betty Ikalany mentioned that there was a project report with information about the auger's materials and properties. Could you provide any information about these?

Answer Summary:

We developed a case hardening procedure using local materials to increase the lifespan of the auger. The screw was placed inside a container and surrounded by charcoal bits. When the entire container and its contents are placed inside a furnace and heated, the carbon from the charcoal diffuses into the surface of the screw. After 1-2 hours, the screw is removed and cooled rapidly (quenched) in a water bucket. This procedure hardens the surface of the screw while leaving the center of the shaft "softer." We were able to double the lifespan of the screws, though no concrete data was collected.

I have attached the report we wrote after our trip. After we tested our procedure at AEST's workshop in January 2014, I put together this documentation with the intention of passing it along to anyone who may work on this project after me. It's an unpolished document really meant to transfer information about the project, the location, the context, etc. I believe it has some information on screw properties, but not much. The material was a low carbon steel, beyond that, I'm not sure we took down any material properties other than physical dimensions. I've also attached a more polished version of this document which has some additional information but also omits some of the sections of the original documentation.

Appendix F: Finite Element Analysis

Introduction

The team used Finite Element Analysis (FEA) to model the horizontal arm of the pin-on-disk machine. This arm will suspend the pin holder assembly over the disk and press the pin onto the spinning disk with a small load. Realistically, the arm will experience downward gravity from its own weight, the pin holder's weight, and any load applied from above; an upward reaction as the pin contacts the disk; and a horizontal load transmitted from the pin's friction against the spinning disk.

The arm was modeled first in SolidWorks, then imported into Abaqus. The model assumes that the vertical loads will be small enough to ignore for the sake of greatly simplifying the simulation. Thus the modeled arm only experiences the transverse force from the pin friction and primarily involves only two dimensions. This report details the bending stresses experienced by the arm due to this force.

The arm will have multiple pivot holes, one of which will have a rod through it connecting it to the vertical supports in the back of the apparatus. This analysis was done to ensure that the stresses on the beam would not be too great when any of the holes are used as the pivot. Having multiple pivot holes allows for greater flexibility during testing.

Free Body Diagram

Figure F 1 shows the free body diagram of the arm under pressure from the clamp. The clamp applies an even pressure over two rectangular areas of the arm. The base pressure of 0.717 psi (4.943 kPa) was multiplied in later tests to measure the effect of higher-than-expected loads. The main boundary condition is a pinned axis at one of the four connector holes, which varied between each test.

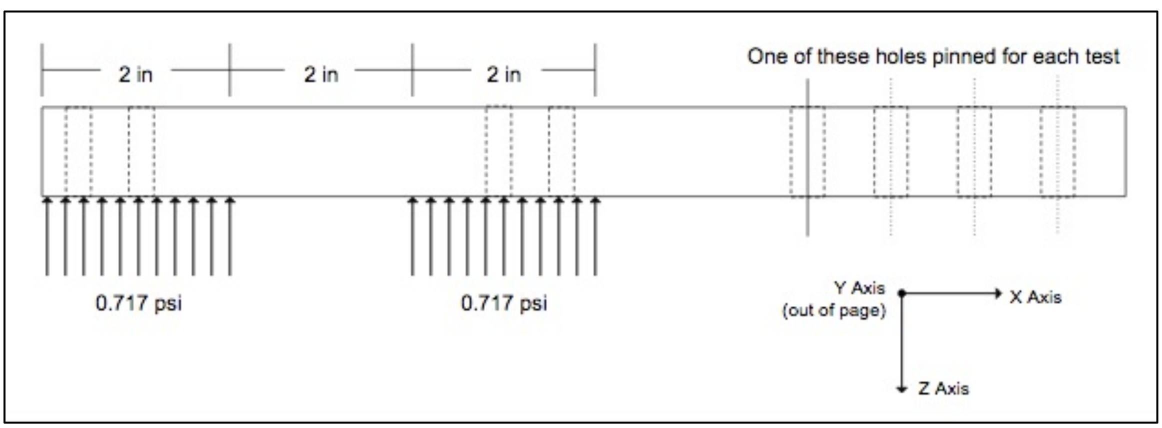


Figure F 1 - Free Body Diagram of Arm, Top View

External Conditions and Load Cases

Figure F 2 details the boundary conditions and loading applied to the arm. One hole at a time was used as a boundary condition for four tests at the calculated load of 0.717 psi (4.943 kPa). These were then repeated for double the load 1.434 psi (9.887 kPa), and five times the load 3.585 psi (24.717 kPa), for a total of 12 tests.

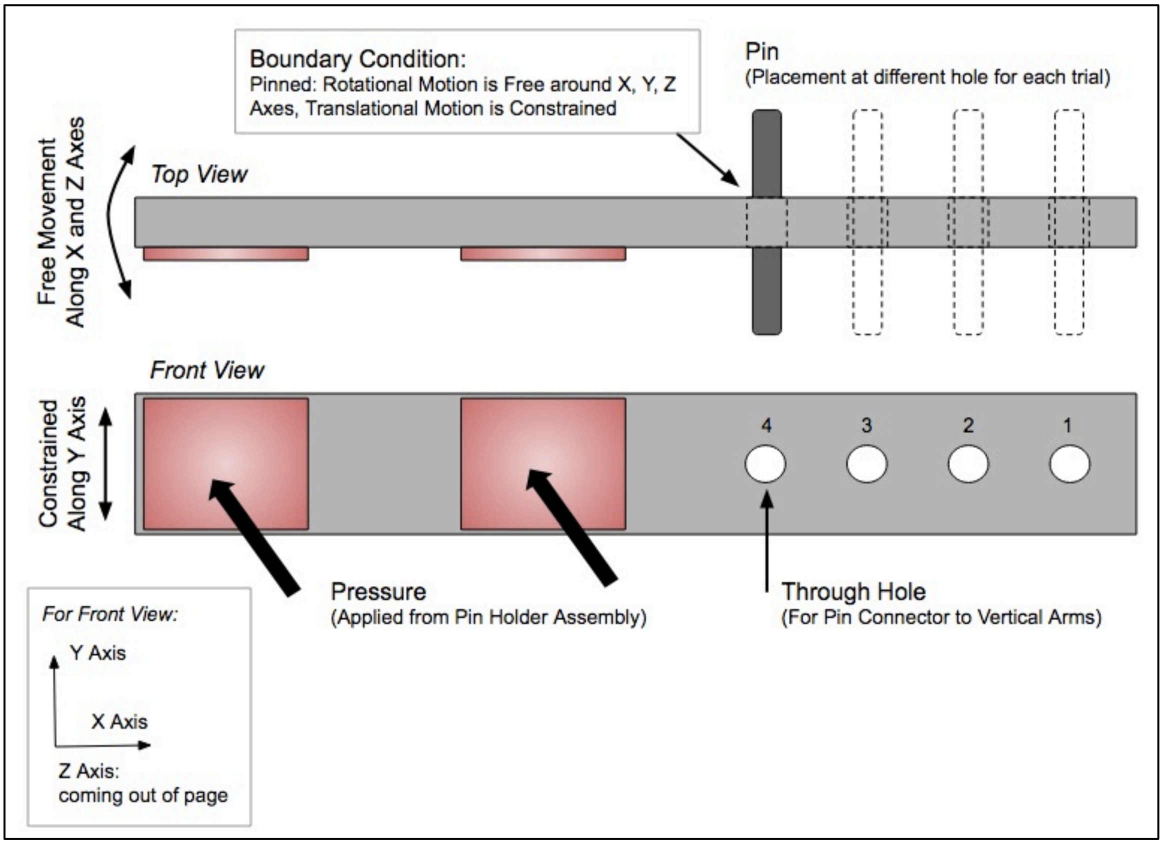


Figure F 2 - Diagram of Arm Showing Top and Side Views

Materials

The arm is made from 2021 Cold Rolled Aluminum. Table F 1 on the next page shows some relevant properties of this material, such as density, elasticity and yield point. The information found in this table was taken from the Mechanical Property Data Sheet for 2021 prepared by the US Air Force Materials Laboratory, Research and Technology Division [18].

Table F 1 - Material Properties of Aluminum 2021

Property	Symbol	Value
Density	ρ	0.101 lb/in^3 (2.795 g/cm^3)
Yield Point in Tension	F_t	58.2 ksi (401.274 MPa)
Yield Point in Compression	F_c	62.3 ksi (429.543 MPa)
Young's Modulus in Tension	E_t	10.1×10^6 psi (69600 MPa)
Young's Modulus in Compression	E_c	11.0 ×10^6 psi (75800 MPa)
Poisson's Ratio [19]	v	0.32

Simplifying Elements

The model was simplified by removing the threading from the holes on the left side of bar that attach the pin holder assembly to the arm. As will be discussed further in the Problems section of this report, all of the supporting subsystem elements had to be removed in order to run the simulation. As the force is primarily one directional in the negative Z direction, this is not a huge issue. There are no significant forces in the Y direction.

Expectations

The expected mode of failure was excessive stress concentration around the hole the pin was placed in. As such, holes 1-4 are critical points on the arm. If the stress on the arm exceeded yield stress, this would be considered a failure. Per Table F 1, the yield point is 58.2 ksi (401.274 MPa) in tension and 62.3 ksi (429.543 MPa) in compression. It is not expected to see failure under the real-world level of load. If there is failure at the higher levels of loading, it would be along the edges of holes 1-4, depending on the trial.

Hand Calculation Model

Figure F 3 on the next page shows the sketched models and equations used to calculate the expected bending stress on the four holes before the simulation. The figure also identifies what the variables of each equation represent.

The drag equation $f_{drag} = \frac{1}{2}C\rho A v^2$ used to approximate the charcoal's effect as a fluid force came from the *Hyperphysics* page "Fluid Friction" [20]. The bending stress equation $\sigma = \frac{Mc}{I}$ and moment of inertia equation $I = \frac{bh^3}{12}$ came from the MECH 114 class and Dr. Shoup's textbook *Design of Machine Elements* [21]. The same book's spreadsheet Module 2-18 also furnished the stress concentration factor calculation for K_c.

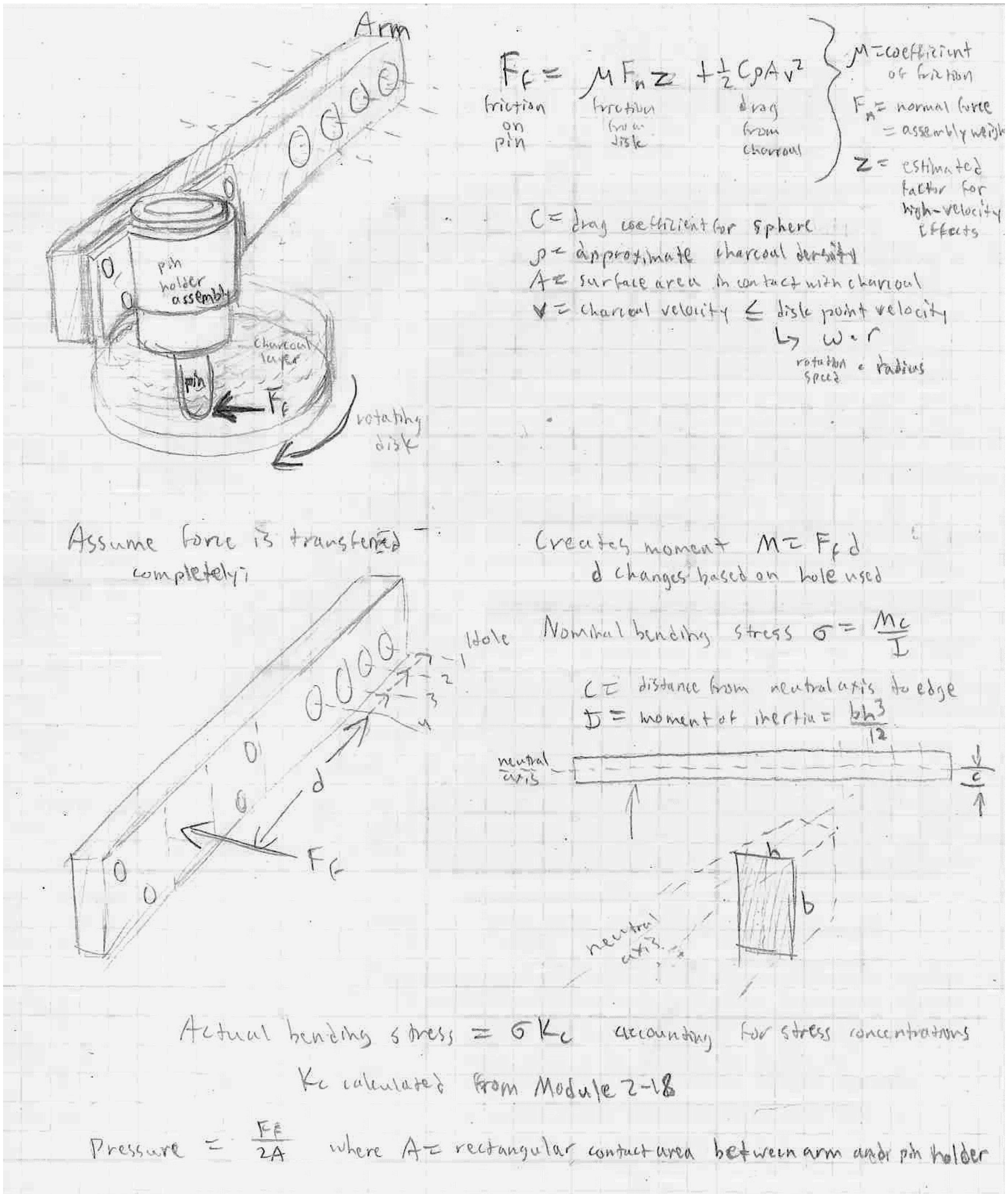


Figure F 3 - Model and Equations Used for Hand Calculations

The charcoal drag component of F_f resulted in a number orders of magnitude lower than the kinetic friction component, so it was judged to be negligible for future calculations.

Figure F 3 on the next page shows the results of the hand calculations for the basic load before and after applying the calculated stress concentration factor. The calculated stresses are lower than the yield stress for the part, so failure is not expected.

Table F 2 - Hand Calculated Results with and without Stress Concentration, 1x Load

Hole	Stress without Concentrations (psi)	Factor K_c	Stress with Concentrations (psi)
1	571.84 (3.942 MPa)	1.94	1109.37 (7.648 MPa)
2	516.00 (3.557 MPa)		1001.04 (6.901 MPa)
3	460.16 (3.172 MPa)		892.71 (6.155 MPa)
4	404.16 (2.786 MPa)		784.07 (5.405 MPa)

Problems

As none of the group members had any previous experience with FEA or Abaqus, much of the time in the lab was spent figuring out what was feasible to model. Initially, the team attempted to model the entire arm subsystem, including the pin, pin holder, and epoxy surrounding the pin. However, it was difficult to model the interaction of different materials, and the stresses were not being transferred correctly through the pin holder to the arm.

As the pin holder weighs less than half a pound, and receives a normal force from the contact of the pin on the disk, it was determined that the weight of the pin holder would not apply a significant downward force to the arm, and was removed from the simulation. Similarly, any mass added to the top of the arm would only be enough to force contact with the disk, and would not be large enough to cause deflection. Once the simulation was simplified to just the forces in the X-Z plane affecting the arm, there were no real problems in the modeling process.

For future modeling, the team is interested in modeling the motion of the charcoal particles on top of the spinning disk as the pin moves through them. However, this type of modeling is not feasible in Abaqus alone. Although Abaqus has some capacity to model soils, it is not particularly robust in this area. From research, it may be possible to model this behavior using Fluent and Abaqus. This further modeling is of great interest, and will be carried out next quarter if possible, once testing has begun.

Modeling Results and Interpretation

Table F 3 shows the results of the finite element analysis modeling. Twelve cases were modeled, for all combinations of the 3 load values and the 4 pin holes.

Table F 3 - Results of Finite Element Analysis Modeling

Hole	Applied Pressure (psi)	Highest Stress (ksi)	Location of Highest Stress
1	0.717 (4.943 KPa)	1.096 (7.556 KPa)	Left side of hole 1
	1.434 (9.887 KPa)	2.191 (15.106 KPa)	
	3.585 (24.717 KPa)	5.479 (37.776 KPa)	
2	0.717 (4.943 KPa)	0.9558 (6.590 KPa)	Left side of hole 2
	1.434 (9.887 KPa)	1.912 (13.182 KPa)	
	3.585 (24.717 KPa)	4.780 (32.956 KPa)	
3	0.717 (4.943 KPa)	0.8275 (5.705 KPa)	Left side of hole 3
	1.434 (9.887 KPa)	1.655 (11.410 KPa)	
	3.585 (24.717 KPa)	4.137 (28.523 KPa)	
4	0.717 (4.943 KPa)	0.7027 (4.844 KPa)	Left side of hole 4
	1.434 (9.887 KPa)	1.405 (9.687 KPa)	
	3.585 (24.717 KPa)	3.513 (24.221 KPa)	

As expected, the highest stress value was seen in the trial for hole 1 with 3.585 (24.717 KPa) applied, with a stress of 5.479 (37.776 KPa) propagated. This is smaller than the yield stress by a factor of 10.

The results for the 0.717 (4.943 KPa) load closely match the hand calculation results from Table F 2 that include the stress concentration factor. This is a good sign that the team's understanding of the problem is accurate and the simulation was set up correctly. A comparison of results can be seen in Table F 4 on the next page. For holes 1, 2, 3, and 4, the percent errors were 1.20%, 4.51%, 7.30%, and 10.37%. The percent error increases as the hole use decreases in distance to the pressure applied.

Table F 4 - Comparison of Theoretical Stress Values and Stress Values from FEA Modeling

Hole	Theoretical Stress Value [with concentrations] (psi)	FEA Stress Value (psi)	Percent Error
1	1109.37 (7.648 MPa)	1096 (7.556 MPa)	1.20
2	1001.04 (6.901 MPa)	955.8 (6.590 MPa)	4.51
3	892.71 (6.155 MPa)	827.5 (5.705 MPa)	7.30
4	784.07 (5.405 MPa)	702.7 (4.844 MPa)	10.37

The graphical results of the FEA for the load case of 0.717 (4.943 KPa) and boundary condition at pin 1 can be seen in Figure F 4. Graphical results for the other loading conditions can be found in Figures F1.1-11 in the Appendix. The figures show color-coded stress distributions throughout the side of the arm, with magnitudes given in units of PSI in the key at the top left.

Notably, the graphical results for trials at the same pin but different load levels appear almost identical. This makes sense because the only parameter changing is the magnitude of the load. As long as the yield point is not reached, the distribution of stress over the arm should look the same, just with a different magnitude.

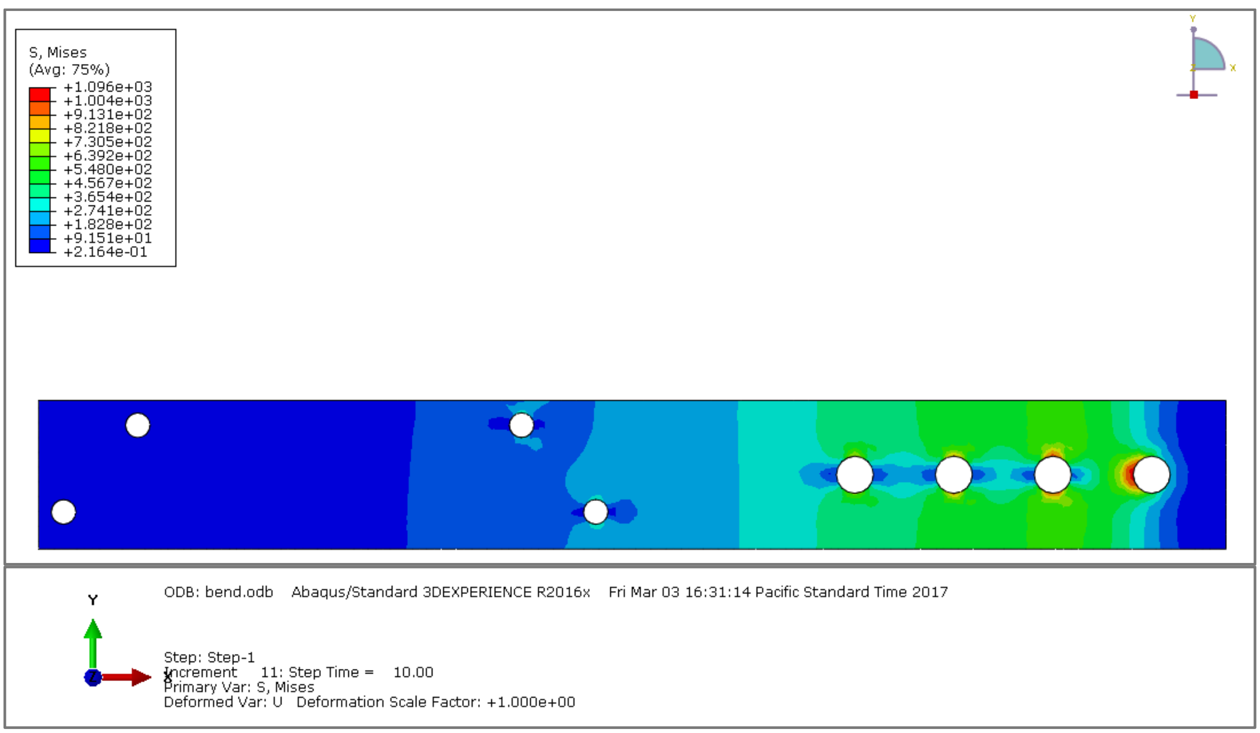


Figure F 4 - FEA of Beam Stress with Pin in Hole 1, 0.717 psi

It should be noted that an increase in pressure led to an increase in maximum stress by the same transformation factor. That is, when pressure was increased by a factor of 2 and then 5, the stress propagated increased by a factor of 2 and then 5. This is exhibited in Table F 1.1, found in the subappendix Appendix F.1 A. The maximum percent error between the ratio of stresses to the ratio of pressures was 0.04562%, for the trial with pin in hole 1 and 1.434 psi (9.887 KPa) applied.

Failure was not seen in any of the trials, as the stresses exhibited were a factor of 10 smaller than yield point (in tension) of 52.8 ksi (401.274 MPa). Similarly, the areas of high stress only extended 0.25 in (0.635 cm) from the side of the pin hole.

These results have several implications for the arm design. The design of the arm is robust enough that the pin can safely be placed at any hole. This is important, as having multiple pin pivot holes allows the sample pin to be placed at multiple locations on the disk, allowing for multiple trials on the same disk. As the yield strength of the part was over 10 times the highest stress reached, it may be possible to reduce the thickness of the arm. As the distribution of high stress was localized around the pin hole, it may also be possible to decrease the distance between pin holes. This is significant, as it would allow for even greater control over the placement of the sample pin on the disk.

Conclusion

The horizontal arm of the pin-on-disk testing apparatus was modeled to explore the stress concentrations around the pin pivot joint holes that connects the vertical supports to the horizontal arm. The forces on the arm were simplified to the force in the X-Z plane for the model. Loads were applied at the expected real-world level, then at 2 and 5 times this load.

The FEA model showed that the part will not fail even at 5 times the expected load. This means that the part thickness can be reduced or the pin joint holes can be placed closer together. Placing the pin holes closer together is beneficial because it allows for more control over the placement of the sample pin on the disk.

Through this exercise, the team gained knowledge of finite element analysis using the Abaqus program. The team began with unrealistic goals for the model, but were able to effectively simplify the model while still producing meaningful results. The team has plans to explore other computer modeling programs to model the motion of the charcoal particles when the sample pin moves through them.

Appendix F.1: Supplementary FEA Data

Table F1. 1 - Comparison of Ratio of Propagated Stress to Ratio of Applied Pressure

Hole	Applied Pressure (psi)	Ratio of Pressure to 0.717 psi [R1]	Highest Stress (ksi)	Ratio of Stress to Stress from 0.717 ksi [R2]	Percent Error between R2 and R1 (%)
1	0.717 (4.943 KPa)	1	1.096 (7.556 KPa)	1.000	0.0000
	1.434 (9.887 KPa)	2	2.191 (15.106 KPa)	1.999	0.0456
	3.585 (24.717 KPa)	5	5.479 (37.776 KPa)	4.999	0.0182
2	0.717 (4.943 KPa)	1	0.9558 (6.590 KPa)	1.000	0.0000
	1.434 (9.887 KPa)	2	1.912 (13.182 KPa)	2.000	0.0209
	3.585 (24.717 KPa)	5	4.780 (32.956 KPa)	5.001	0.0209
3	0.717 (4.943 KPa)	1	0.8275 (5.705 KPa)	1.000	0.0000
	1.434 (9.887 KPa)	2	1.655 (11.410 KPa)	2.000	0.0000
	3.585 (24.717 KPa)	5	4.137 (28.523 KPa)	4.999	0.0121
4	0.717 (4.943 KPa)	1	0.7027 (4.844 KPa)	1.000	0.0000
	1.434 (9.887 KPa)	2	1.405 (9.687 KPa)	1.999	0.0285
	3.585 (24.717 KPa)	5	3.513 (24.221 KPa)	4.999	0.0142

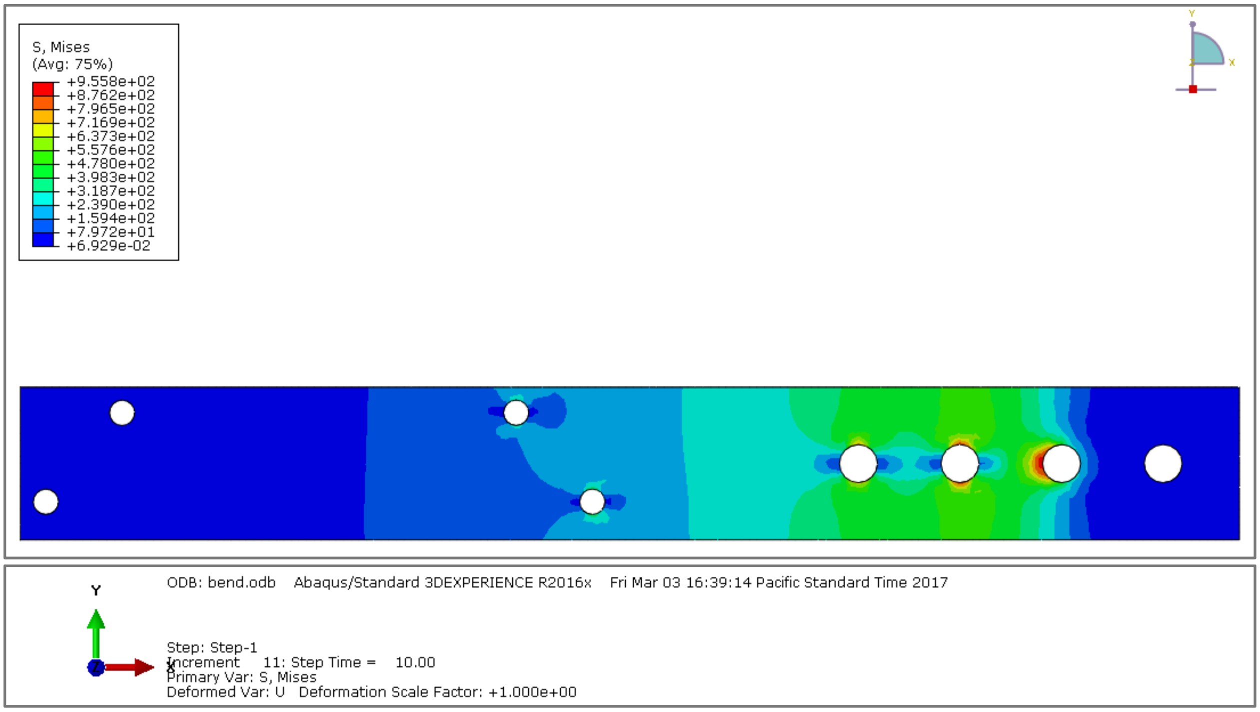


Figure F1. 1 - FEA of Beam Stress with Pin in Hole 2, 0.717 psi

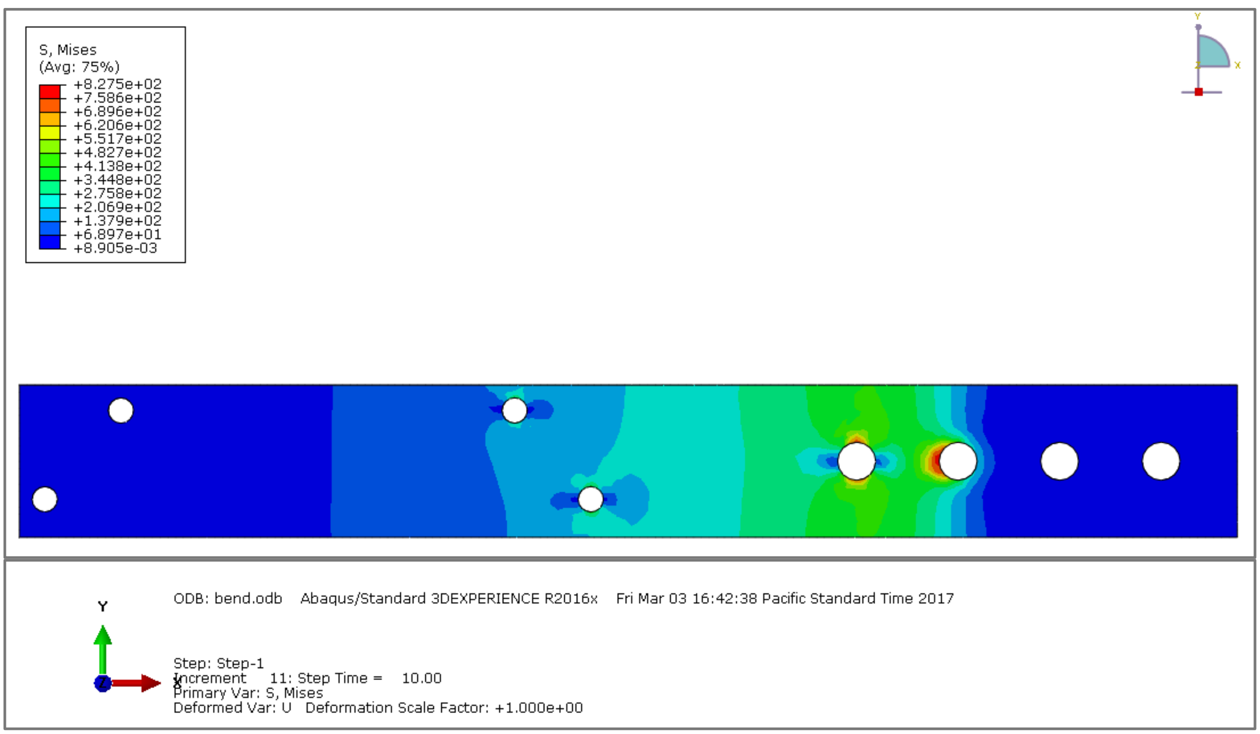


Figure F1. 2 - FEA of Beam Stress with Pin in Hole 3, 0.717 psi

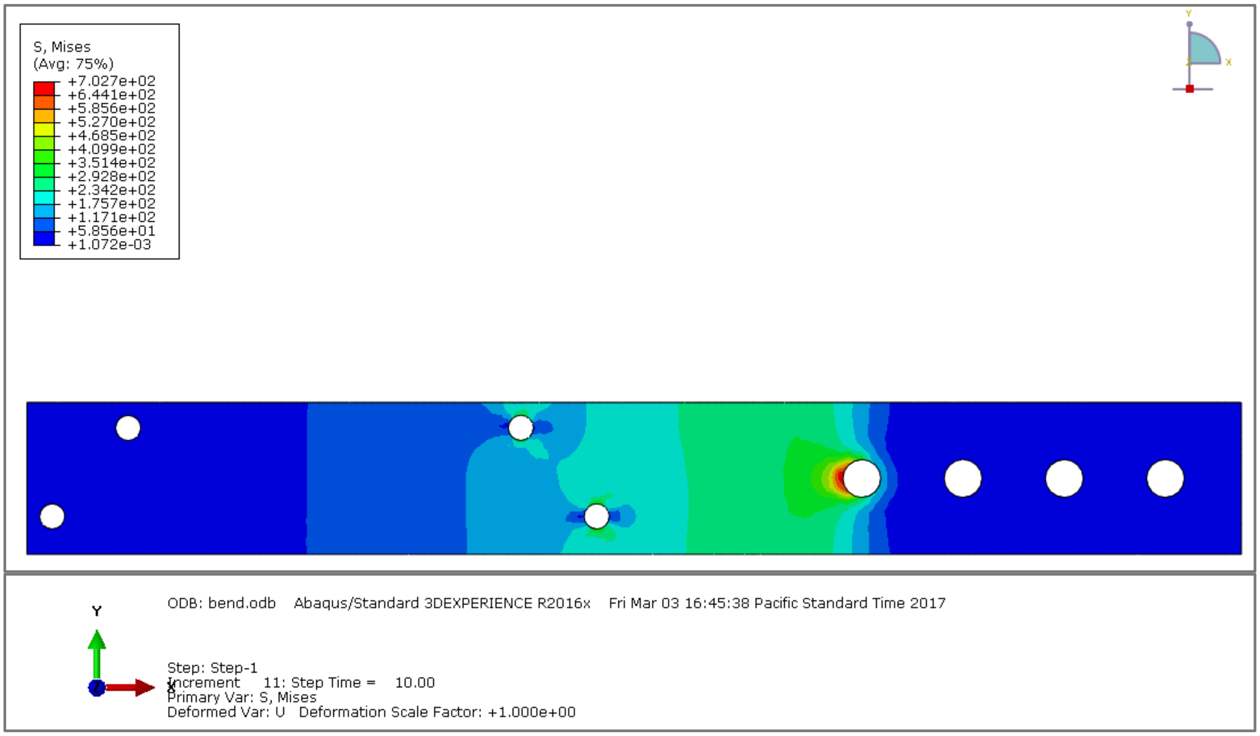


Figure F1. 3 - FEA of Beam Stress with Pin in Hole 4, 0.717 psi

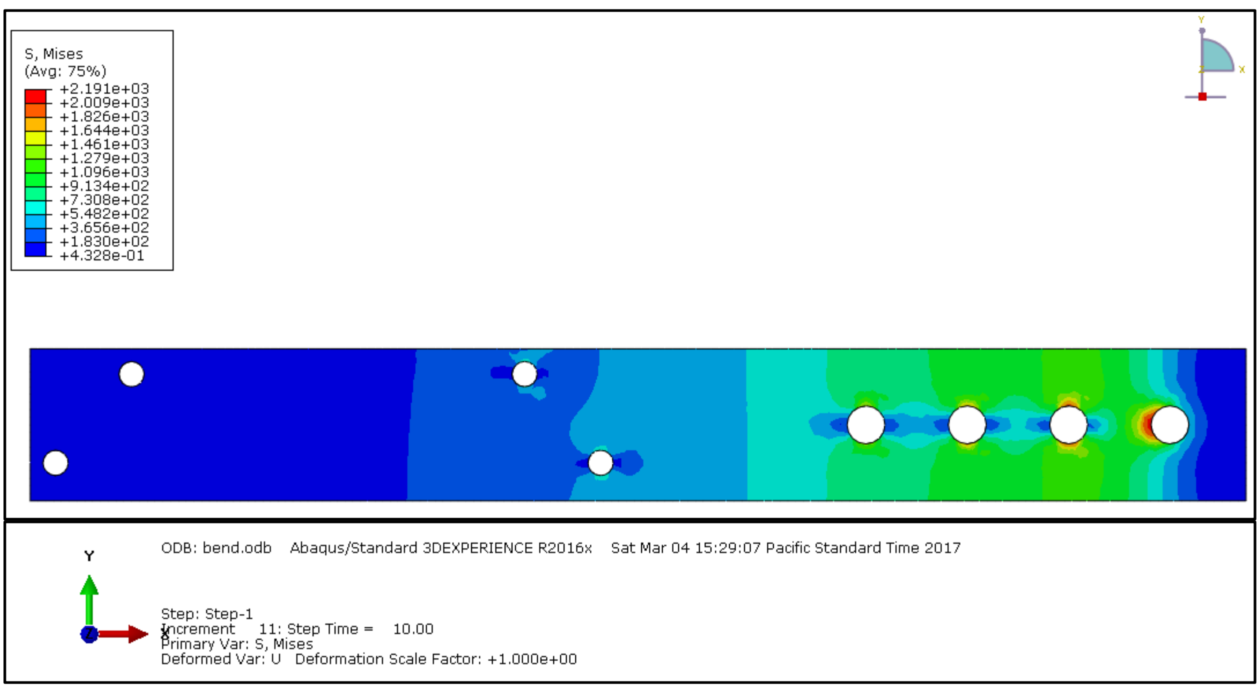


Figure F1. 4 - FEA of Beam Stress with Pin in Hole 1, 1.434 psi

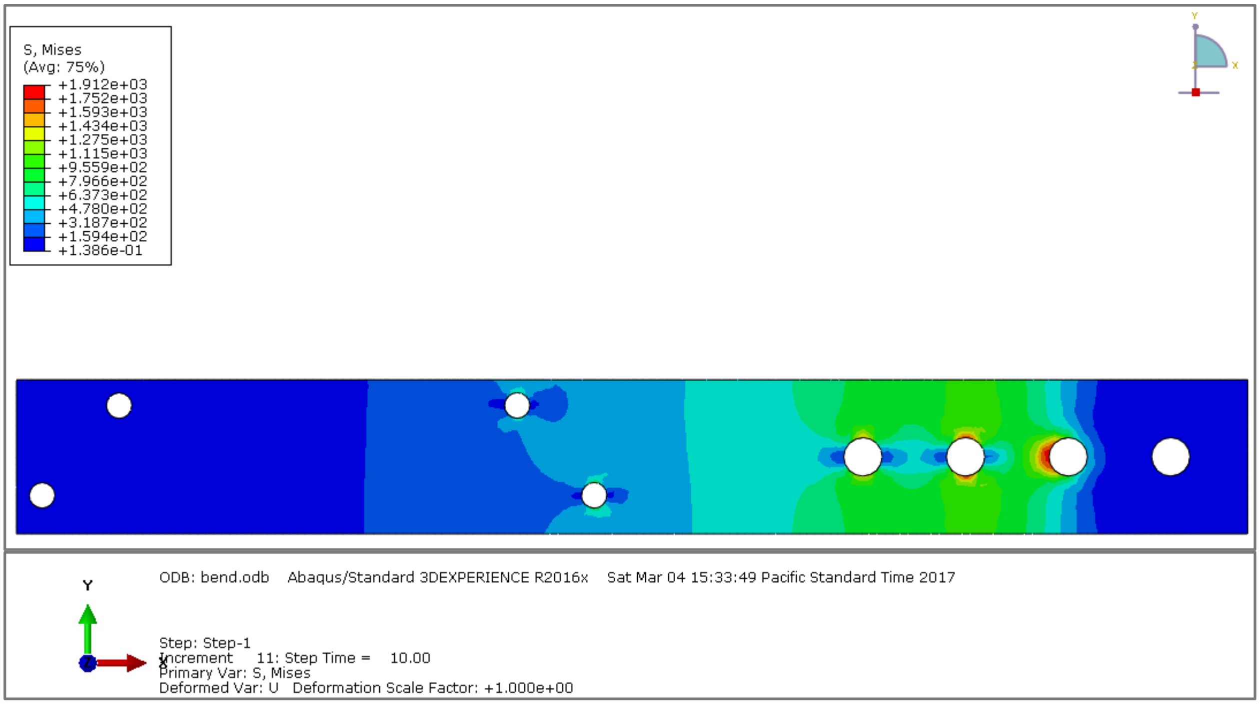


Figure F1. 5 - FEA of Beam Stress with Pin in Hole 2, 1.434 psi

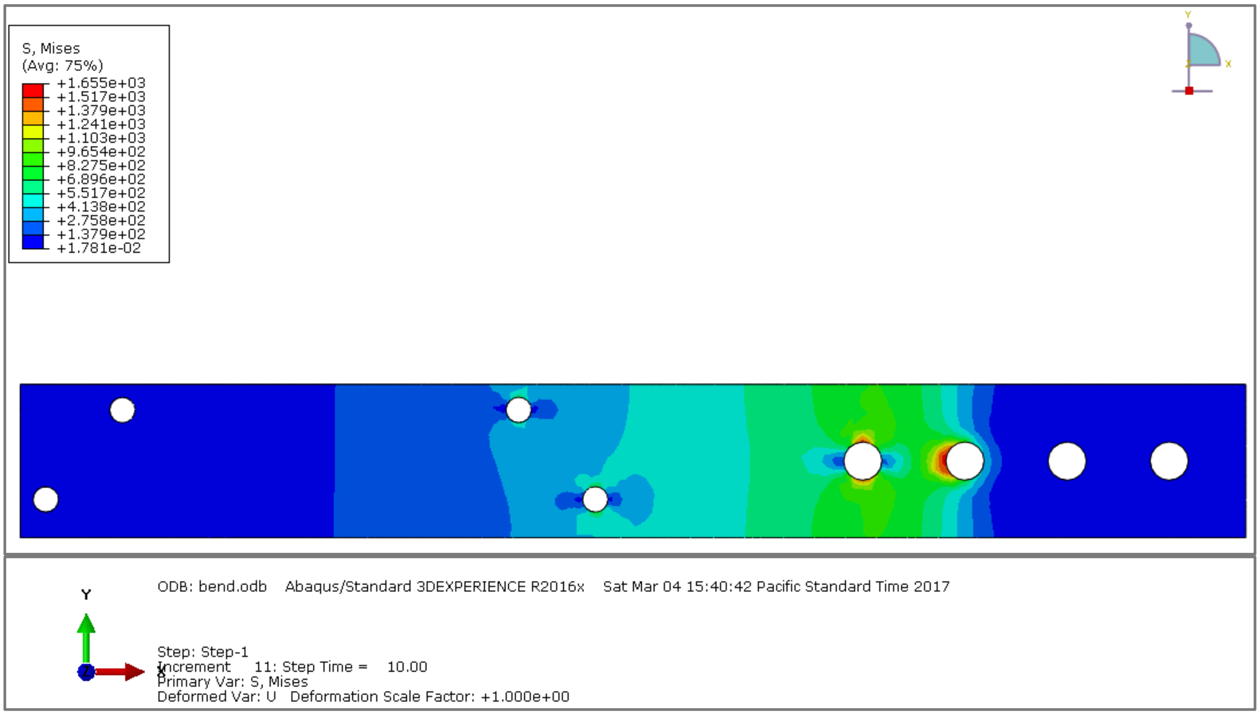


Figure F1. 6 - FEA of Beam Stress with Pin in Hole 3, 1.434 psi

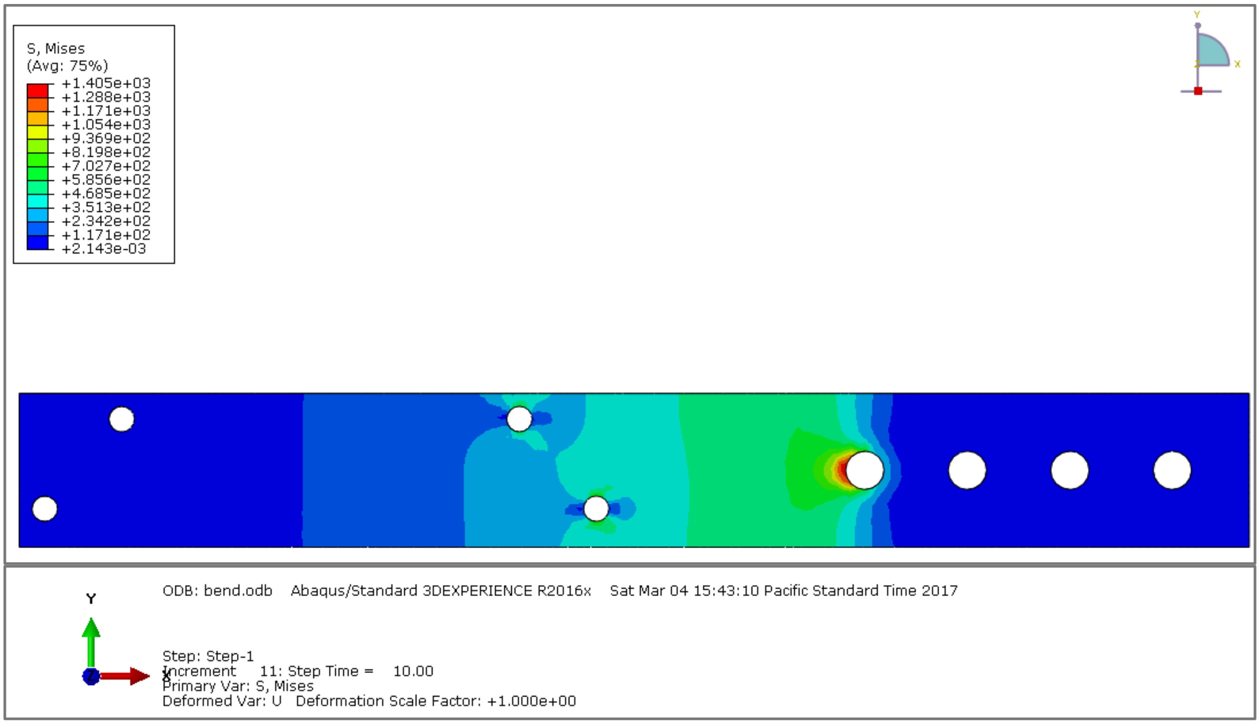


Figure F1. 7 - FEA of Beam Stress with Pin in Hole 4, 1.434 psi

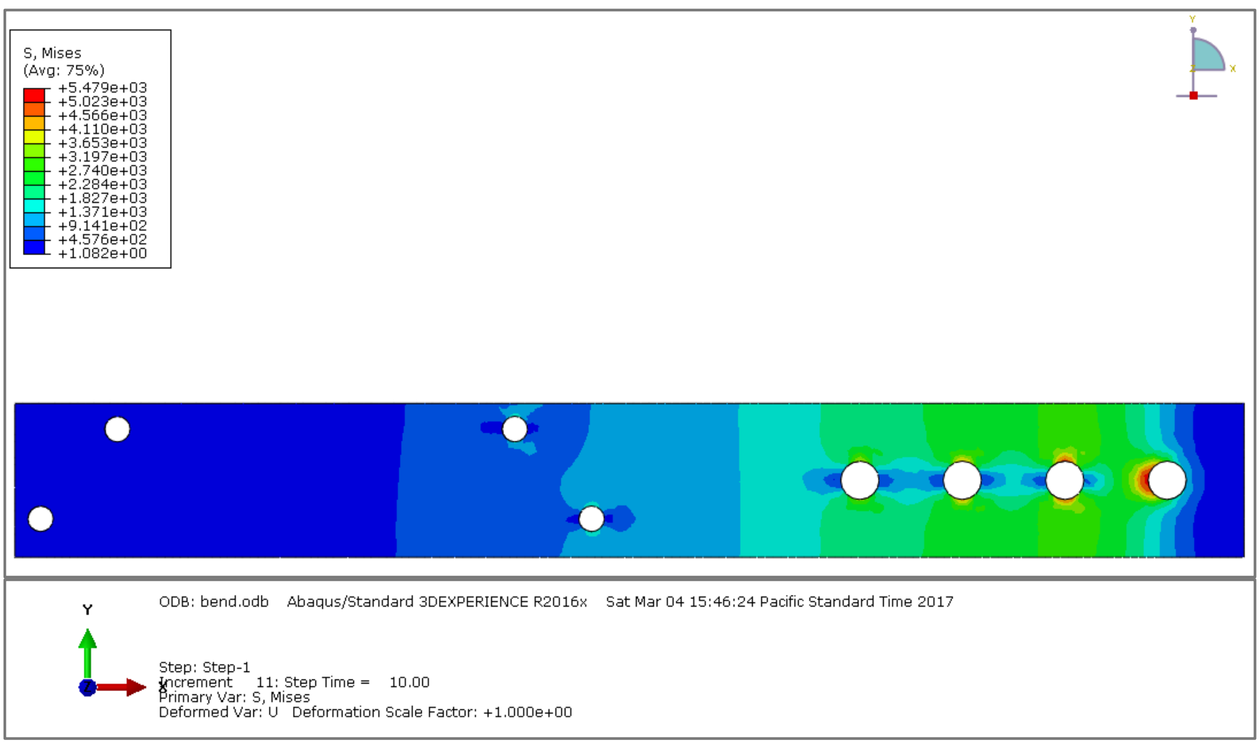


Figure F1. 8 – FEA of Beam Stress with Pin in Hole 1, 3.585 psi

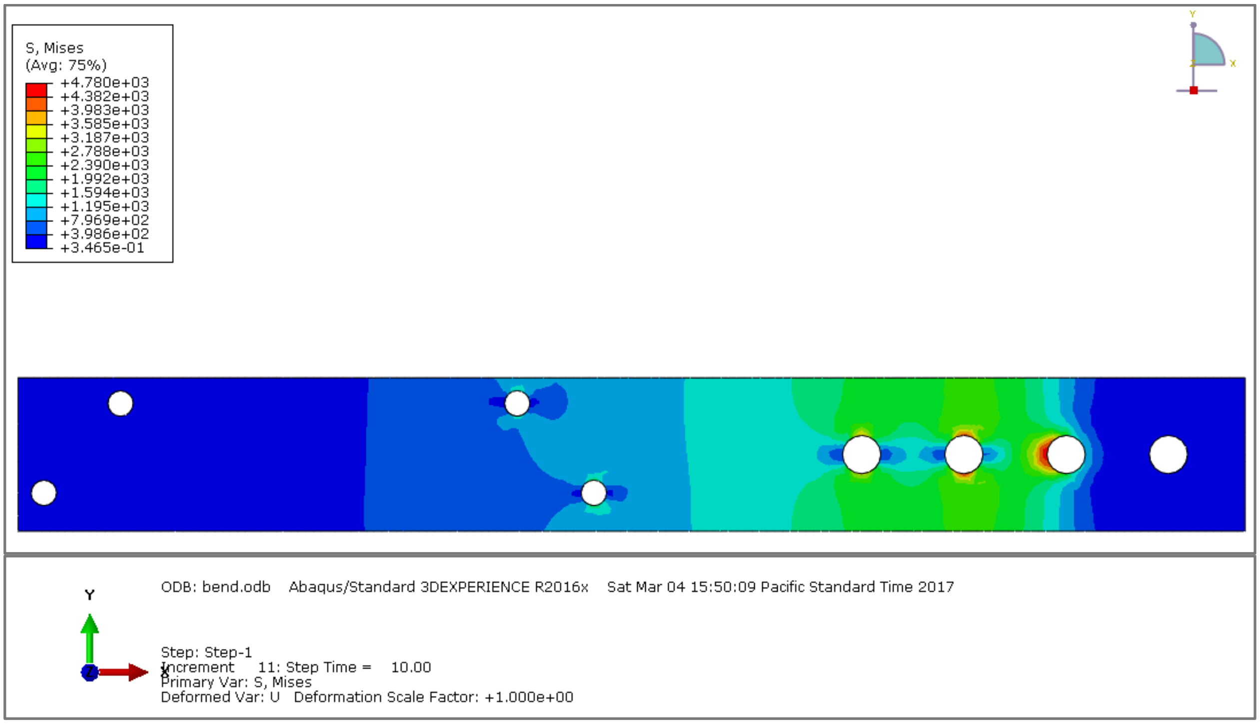


Figure F1. 9 - FEA of Beam Stress with Pin in Hole 2, 3.585 psi

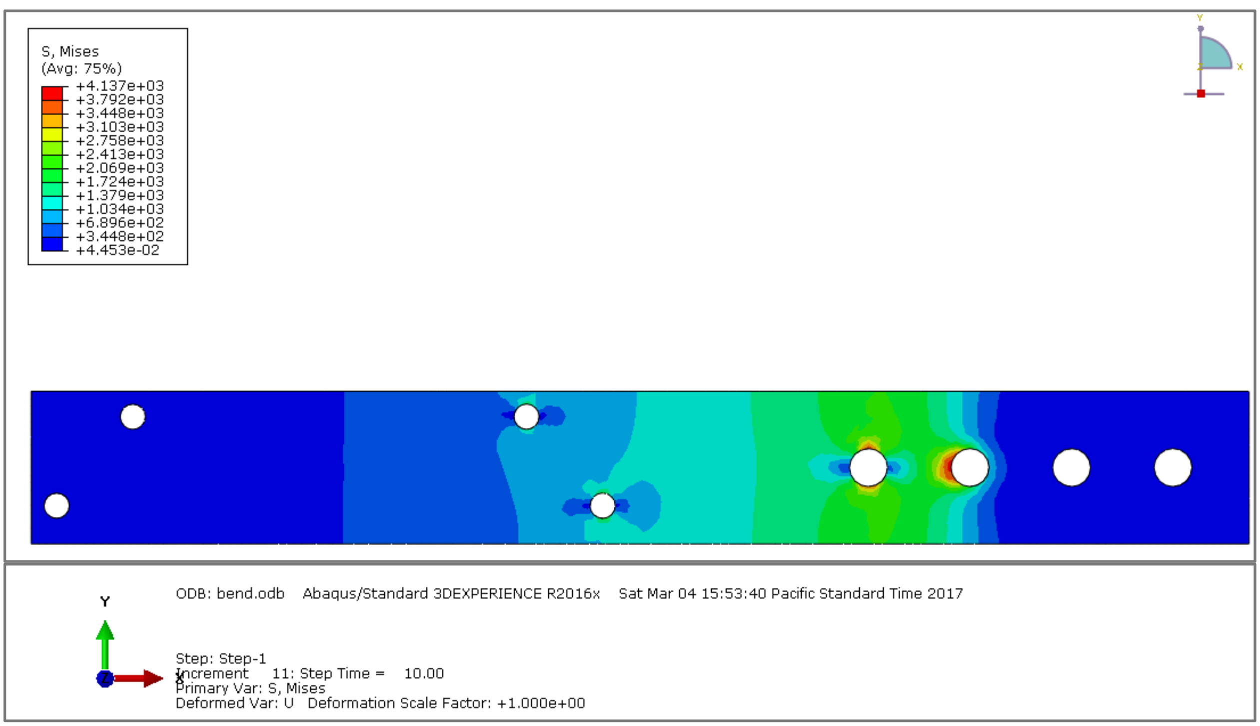


Figure F1. 10 - FEA of Beam Stress with Pin in Hole 3, 3.585 psi

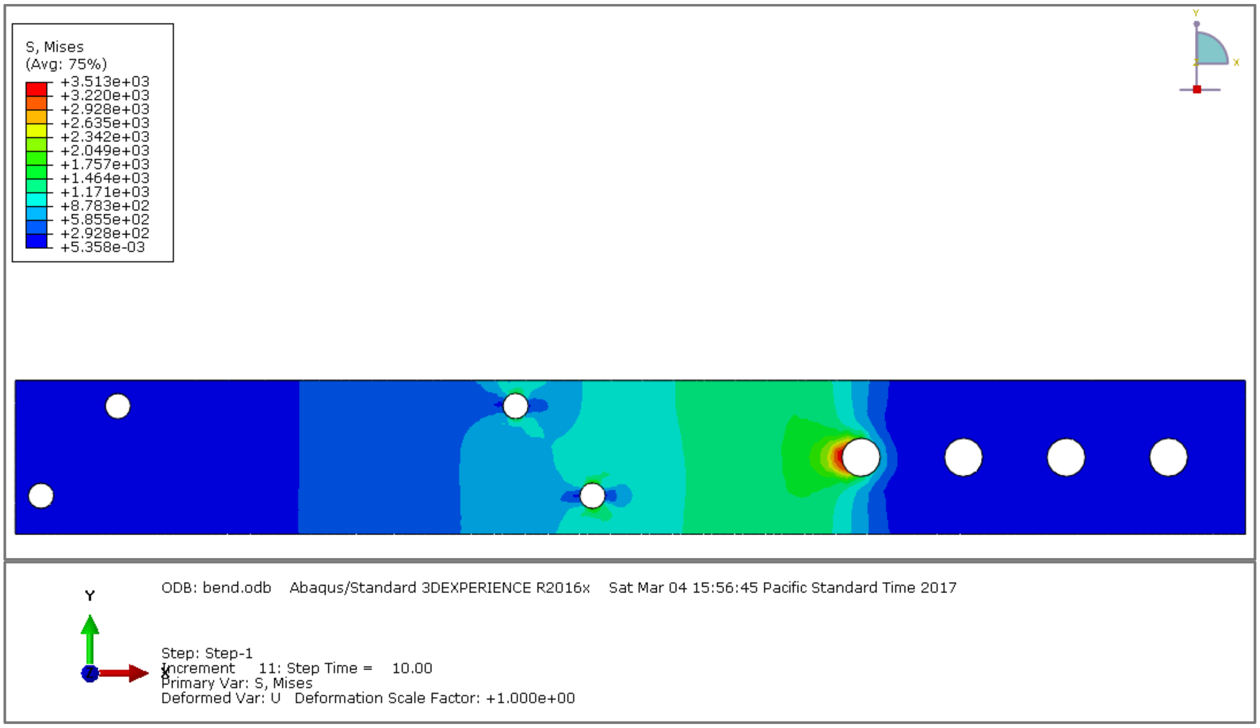


Figure F1. 11 - FEA of Beam Stress with Pin in Hole 4, 3.585 psi

Appendix G: Microscopy and Microhardness Results

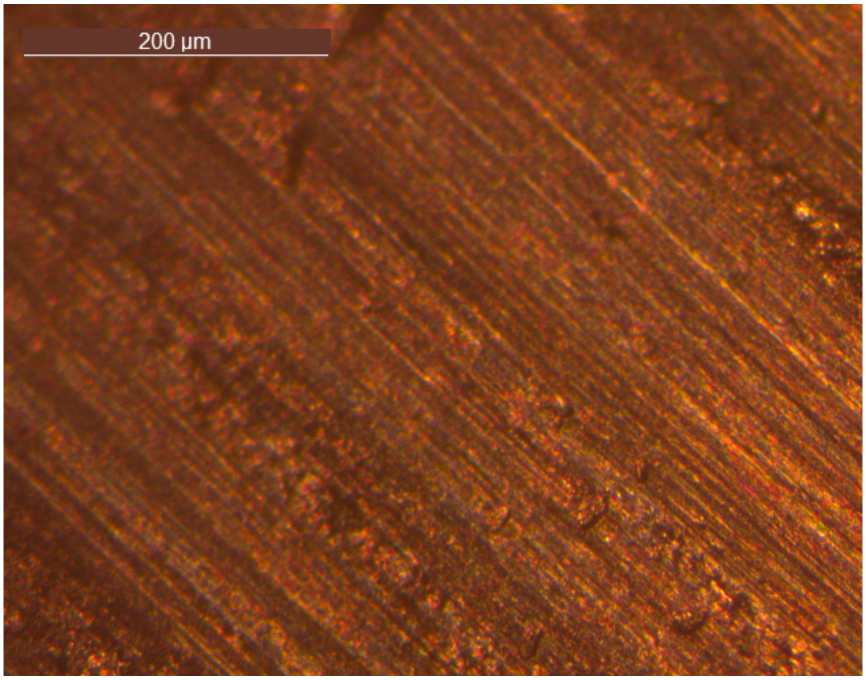


Figure G 1 - 100x microscopy view of 1018 steel sample after pin-on-disk testing.

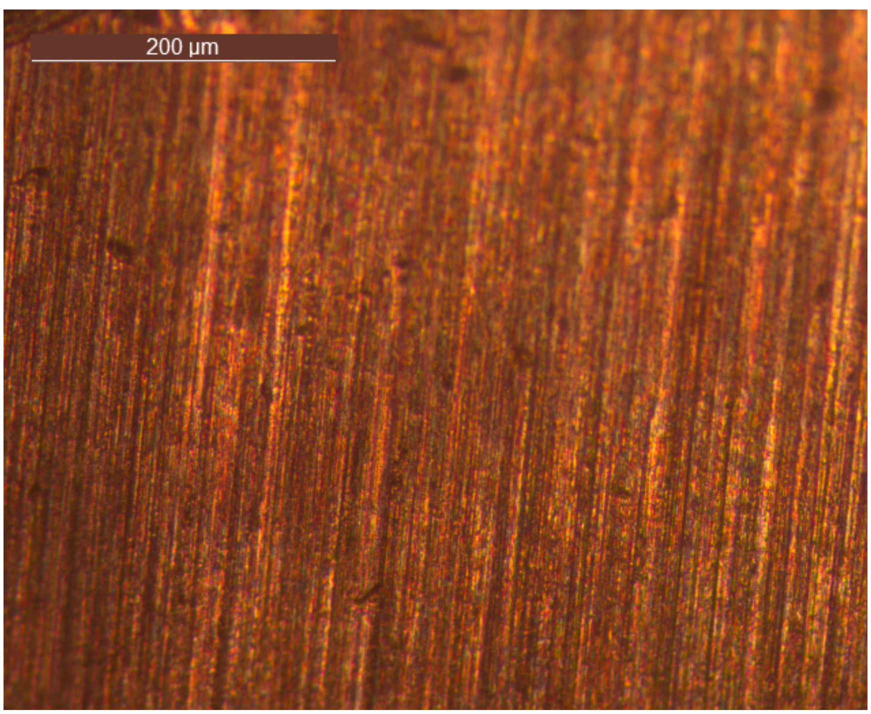


Figure G 2 - 100x microscopy view of 1214 steel sample after pin-on-disk testing.

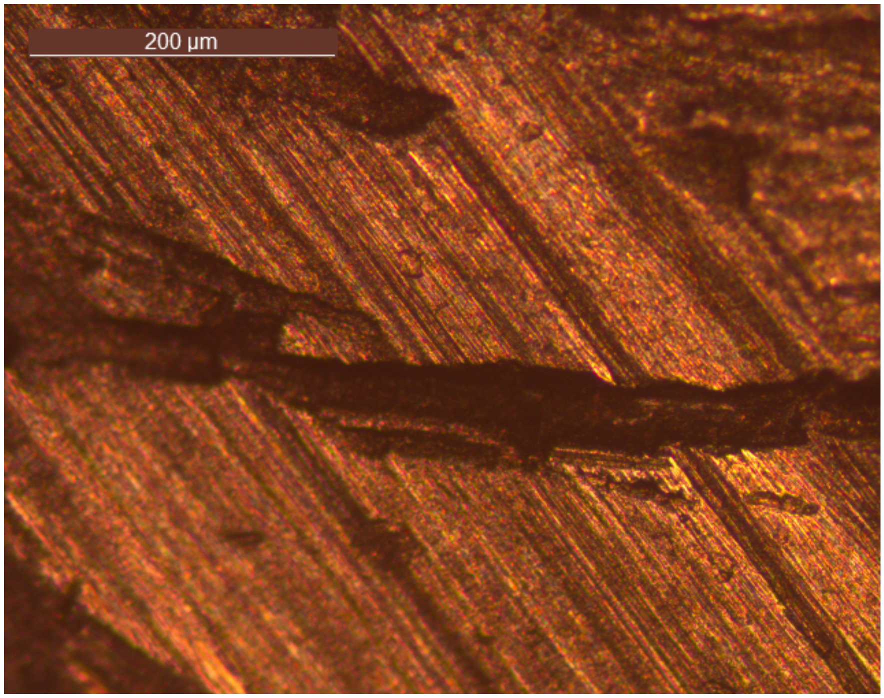


Figure G 3 - 100x microscopy view of 1045 steel sample after pin-on-disk testing.

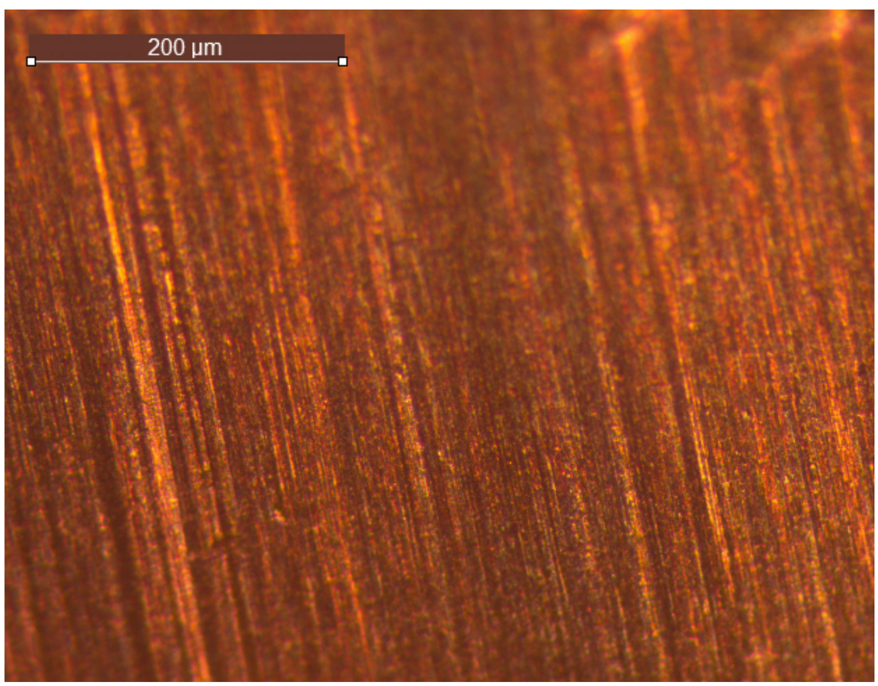


Figure G 4 - 100x microscopy view of 8620 steel sample after pin-on-disk testing.

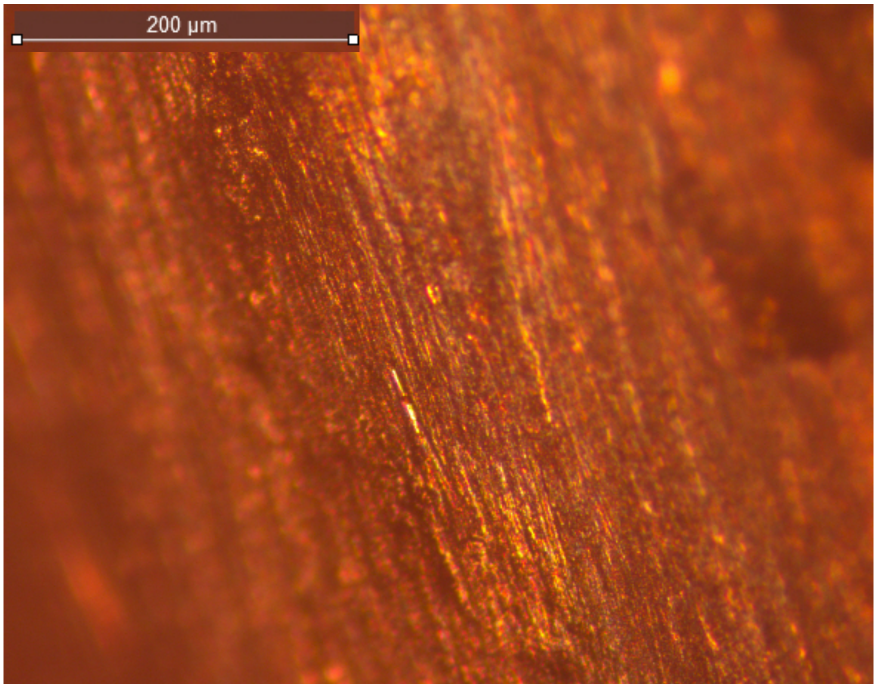


Figure G 5 - 100x microscopy view of 1018 steel sample (case depth 0.0508 cm and water quenched) after pin-on-disk testing.

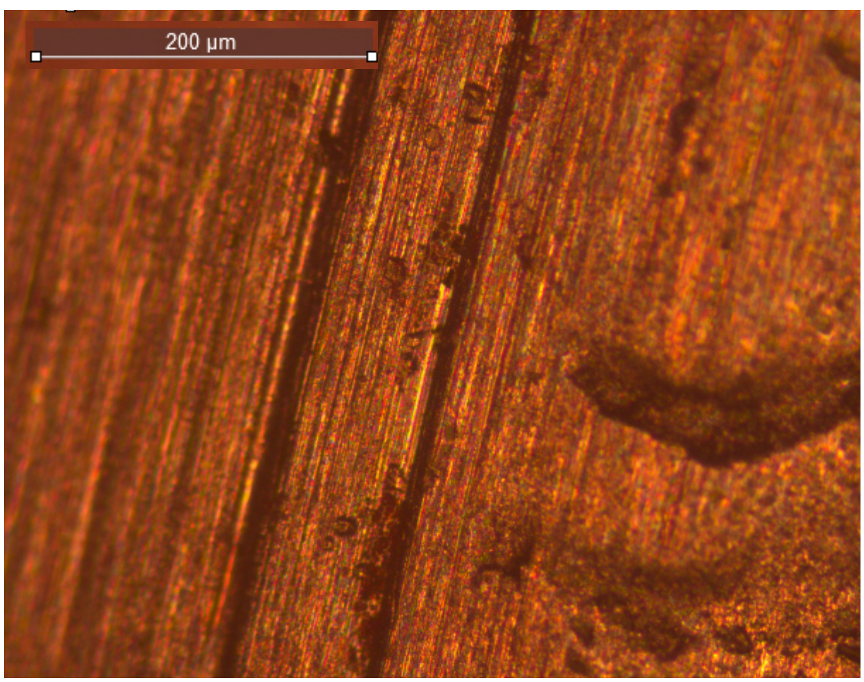


Figure G 6 - 100x microscopy view of 1018 steel sample (case depth 0.0508 cm and oil quenched) after pin-on-disk testing.

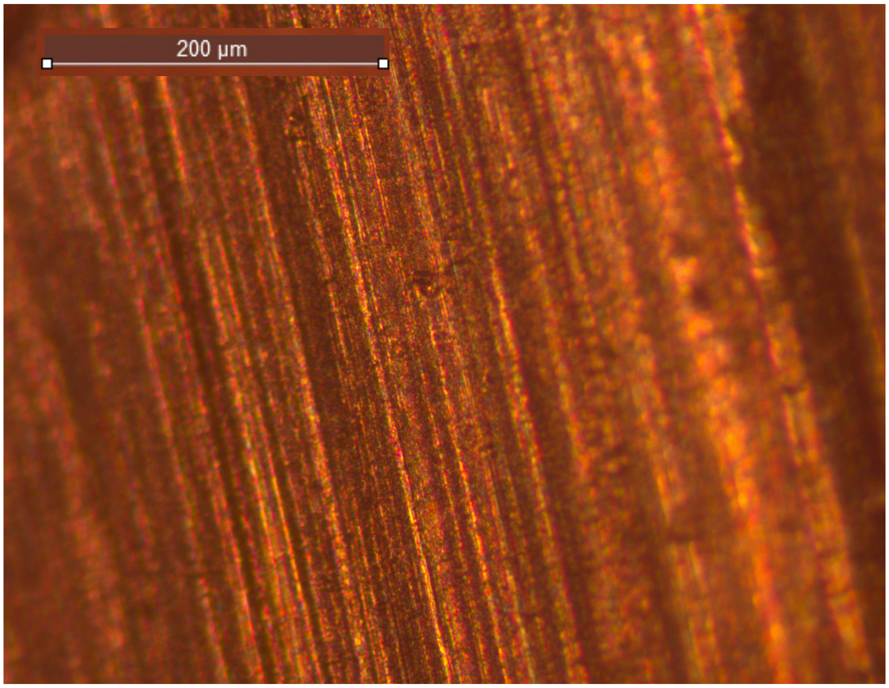


Figure G 7 - 100x microscopy view of 1018 steel sample (case depth 0.0706 cm and water quenched) after pin-on-disk testing.

Due to the rounded shape of the samples, getting a clear picture under microscopy was difficult and in some cases impossible. The microscope is designed to focus on a flat plane, and unfortunately the rounded tip does not readily provide this. However, the 3-body abrasion can still be seen in the areas that are in focus.

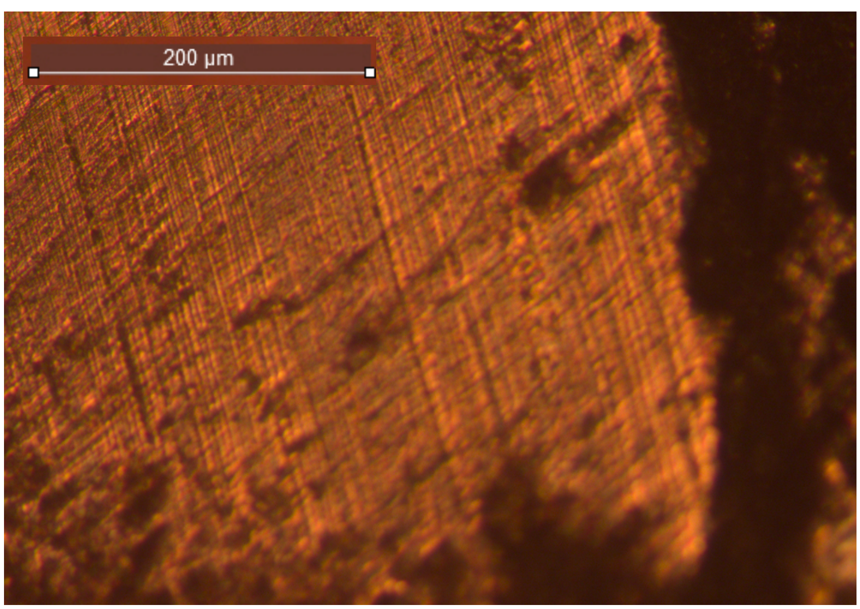


Figure G 8 - 100x microscopy view of 1018 steel sample (case depth 0.0706 cm and oil quenched) after pin-on-disk testing.

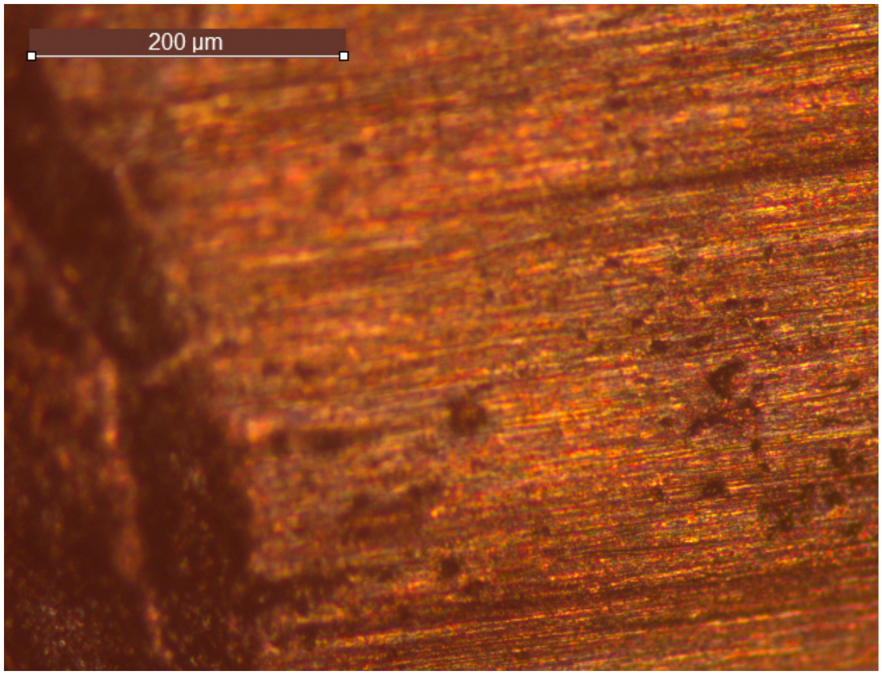


Figure G 9 - 100x microscopy view of 1018 steel sample (case depth 0.0914 cm and water quenched) after pin-on-disk testing.

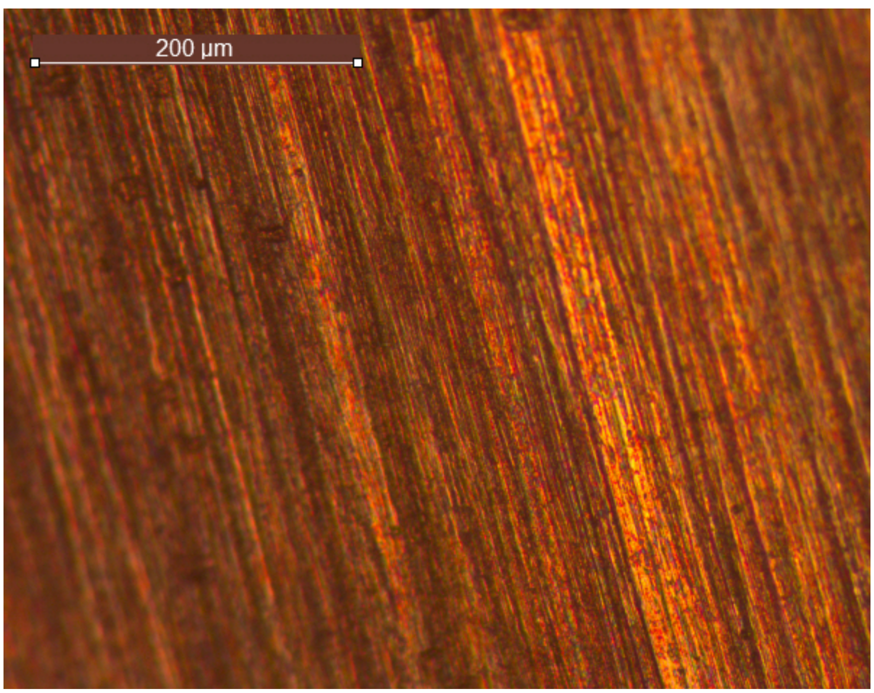


Figure G 10 - 100x microscopy view of 1018 steel sample (case depth 0.0914 cm and oil quenched) after pin-on-disk testing.

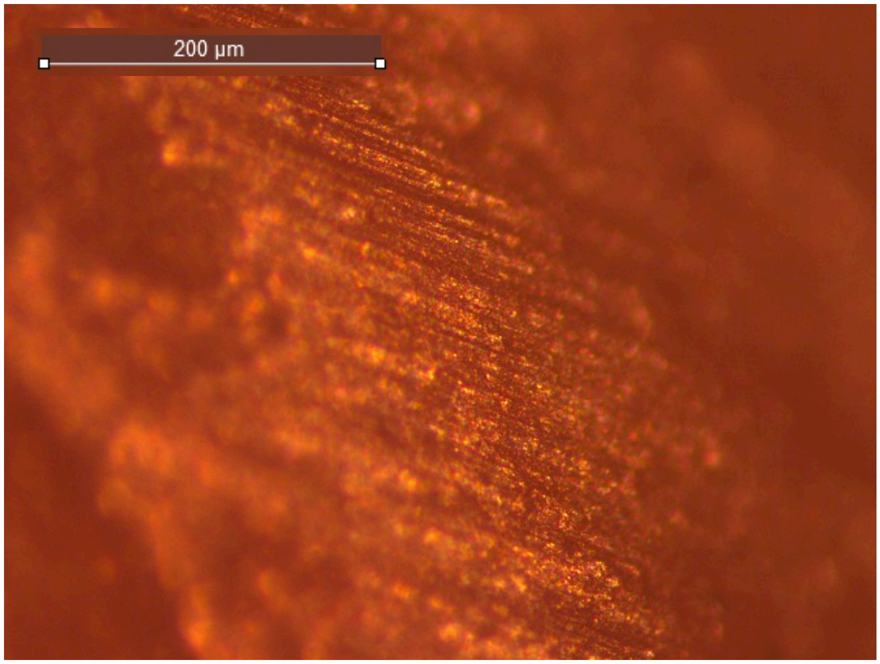


Figure G 11 - 100x microscopy view of 1018 steel sample (case depth 0.1016 cm and water quenched) after pin-on-disk testing.

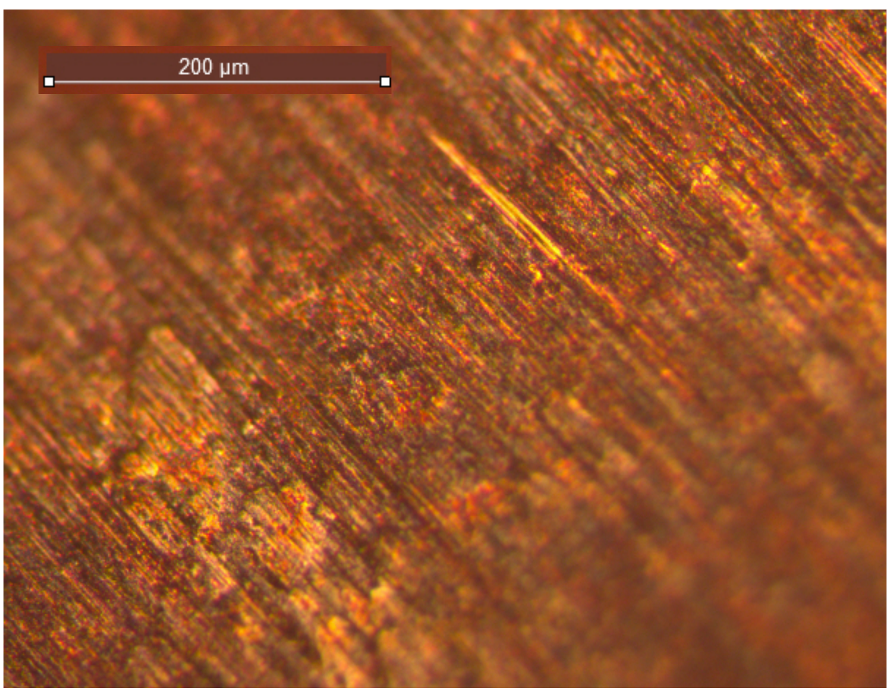


Figure G 12 - 100x microscopy view of 1018 steel sample (case depth 0.1016 cm and oil quenched) after pin-on-disk testing

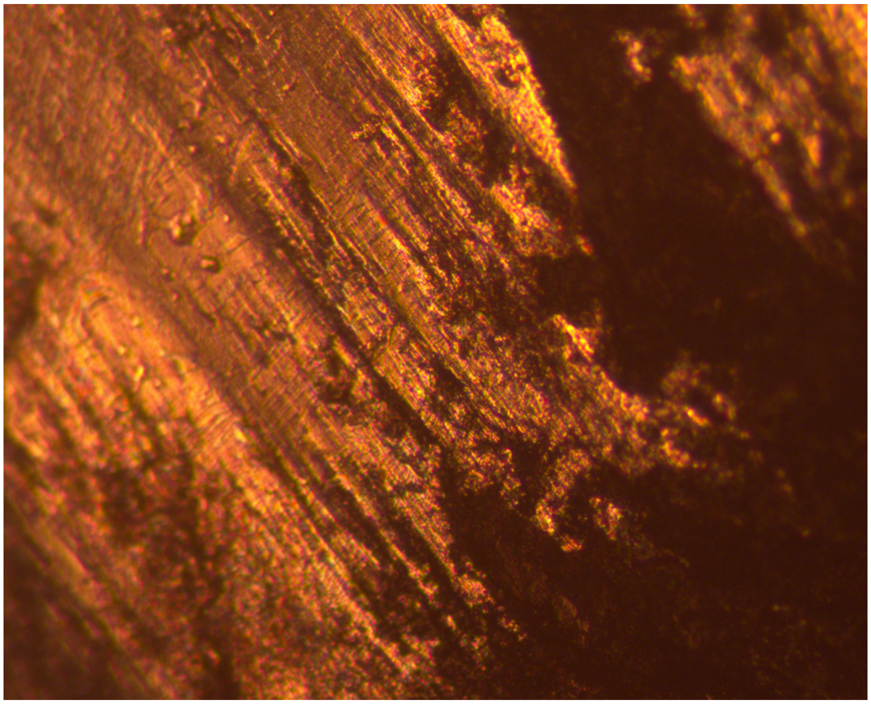


Figure G 13 - 100x microscopy view of 1018 steel sample (case depth 0.1143 cm and water quenched) after pin-on-disk testing.

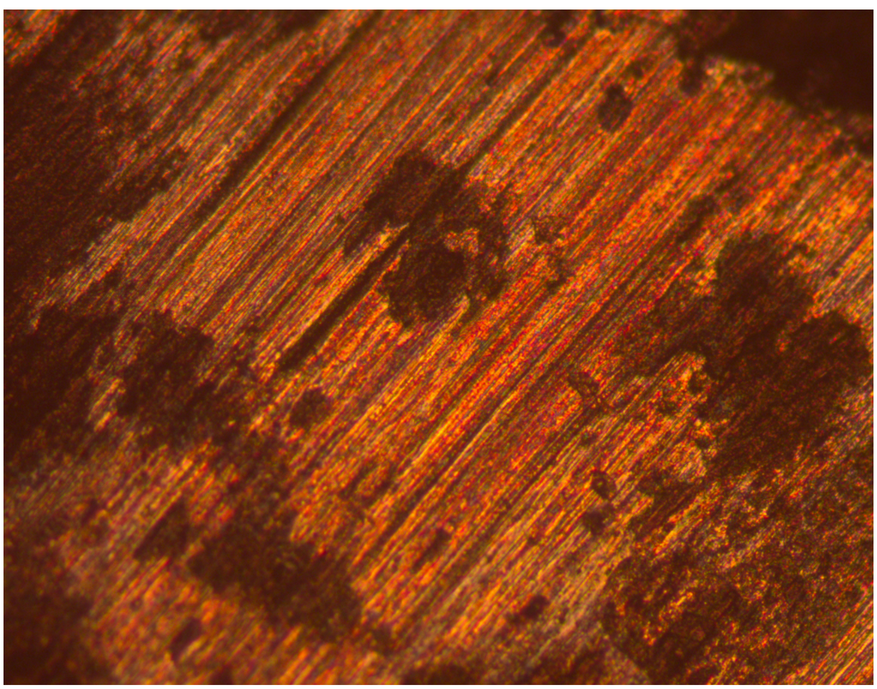


Figure G 14 - 100x microscopy view of 1018 steel sample (case depth 0.1143 cm and oil quenched) after pin-on-disk testing.

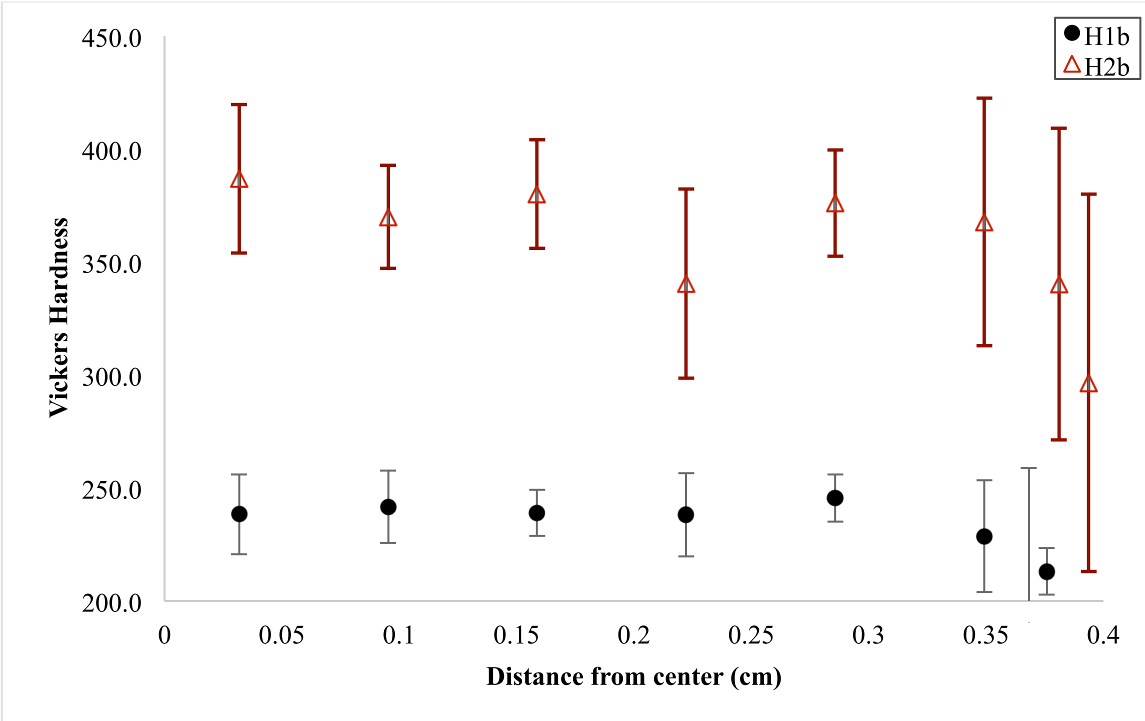


Figure G 15 – Vickers hardness testing results for process control specimens H1 and H2.

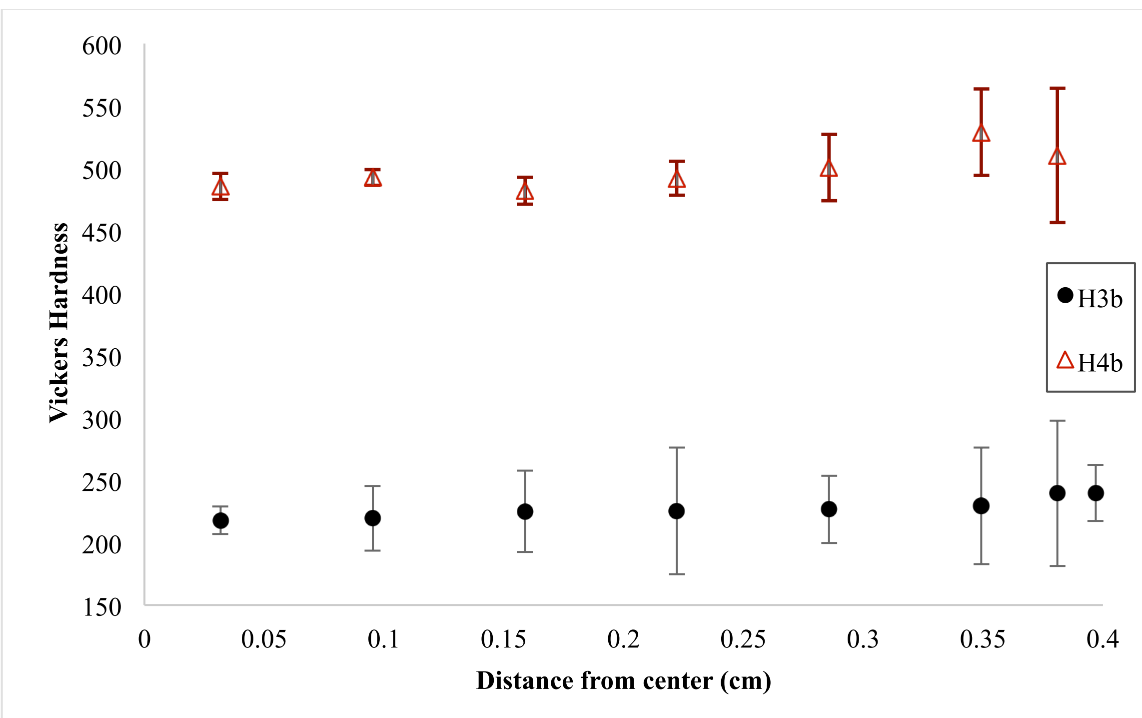


Figure G 16 - Vickers hardness testing results for process control specimens H3 and H4.

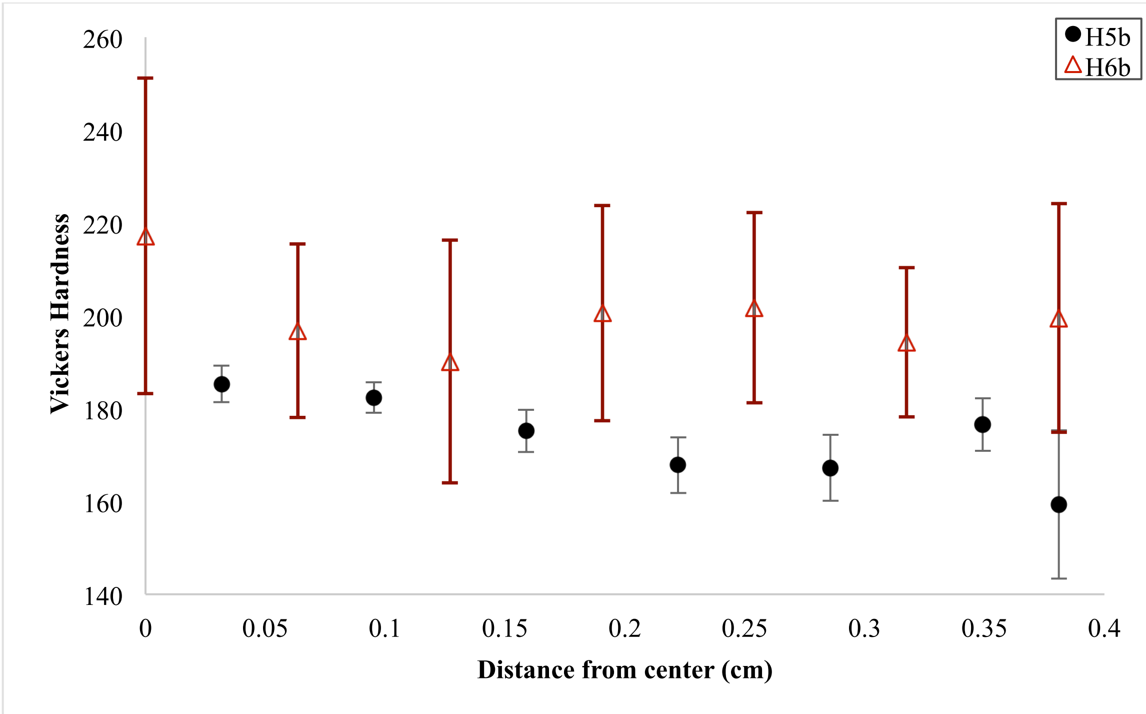


Figure G 17 - Vickers hardness testing results for process control specimens H5 and H6.

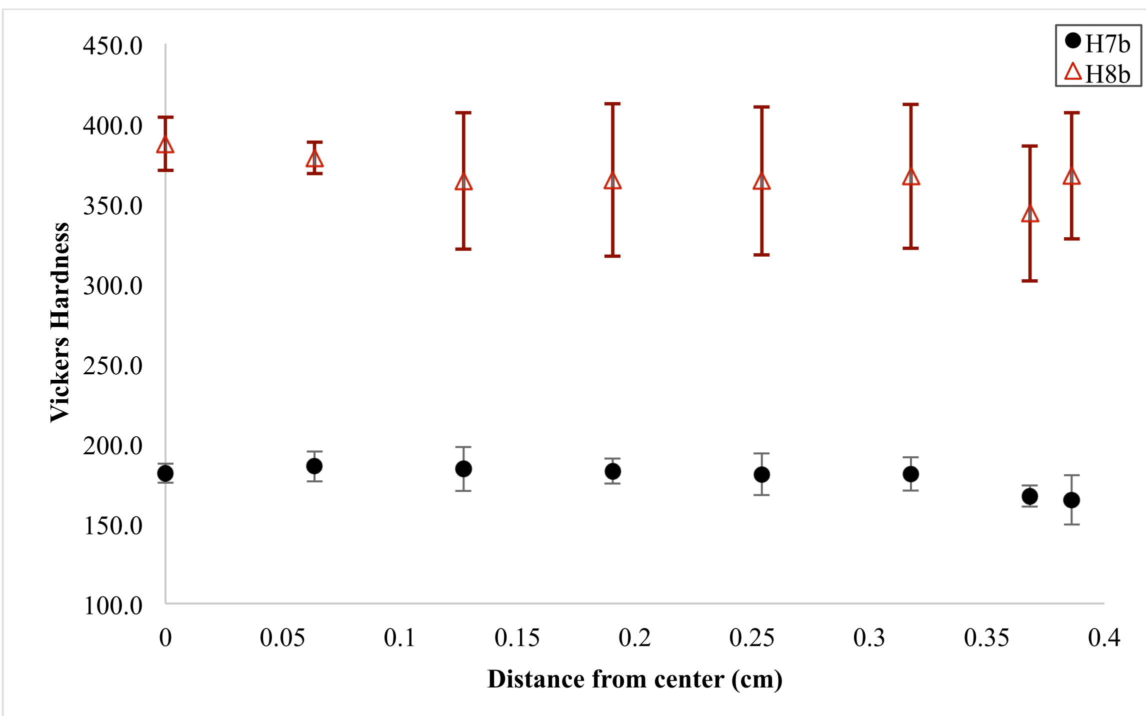


Figure G 18 - Vickers hardness testing results for process control specimens H7 and H8.

Appendix H: Senior Design Competition Slides

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Extrusion Auger Improvement Project

Maureen O'Neill
Mechanical Engineering Major
Aaron Wagner
Mechanical Engineering Major

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Presentation Outline

- Project Team and Partners
- Project Background
- Project Goals
- Subsystems
- Heat Treatment
- Experimental Results
- Conclusions
- Project Future

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Project Team, Partners, & Background

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Team Members and Partners

- Student Members
  - Aaron Wagner, MECH
  - Maureen O'Neill, MECH
- Advisor
  - Dr. Panthea Sepehrband, Dept. of Mechanical Engineering
- Social Enterprise Partner
  - Appropriate Energy Saving Technologies Limited (AEST)
  - Betty Ikalany, CEO

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AEST

- Based in Soroti, Uganda
- Manufactures and sells recycled charcoal and affordable cookstoves to low-income locals

Images via AEST

Soroti Highlighted in orange

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Benefits

- Recycled briquettes:
  - Provide fuel source without most health risks of wood coal
  - Save trees and the time taken to chop them
  - Are 25% cheaper than wood briquettes

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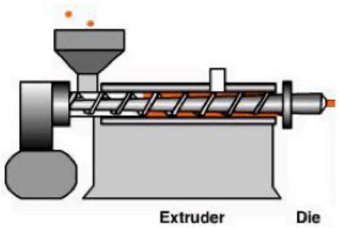
The Extrusion Process

- Shapes any moldable material into long, even bar
- Auger screw pushes material through barrel out of hole (die)
- AEST extrudes charcoal mix into briquettes



Animation by Polymer Science Learning Center

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Design Problem

- Augers currently wear down very quickly from friction with charcoal and extruder
- Three working days of use
- Extrusion machines go unused
  - Not enough augers at once

Top: New Auger
Bottom: Twice-Repaired Auger
[Wang 2015]

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Project History

- Pre-2010
  - Betty Ikalany begins collaborating with the MIT D-Labs
- Spring 2015
  - MIT student Lindsey Wang designs case-hardening method and machine repairs
- 2015-16
  - MIT Engineers without Borders improves furnace and charcoal dust production methods

MIT EWB-constructed furnace

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What is Needed

- Previous experiments only investigated hardness of different quenchants
- Need quantitative wear data
- Is hardness enough to resist wear?
  - Possibility of corrosion
- Data gathered during design informs later project teams

Auger being removed from furnace, 2015

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Project Goals

- Reduce wear on the augers to increase their lifespan
- Achieve same or better lifespan-to-cost ratio
- Determine wear mechanism
  - Build testing apparatus

AEST Employee holding three augers
[engineeringforchange.org]

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Apparatus

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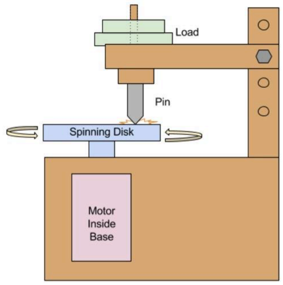
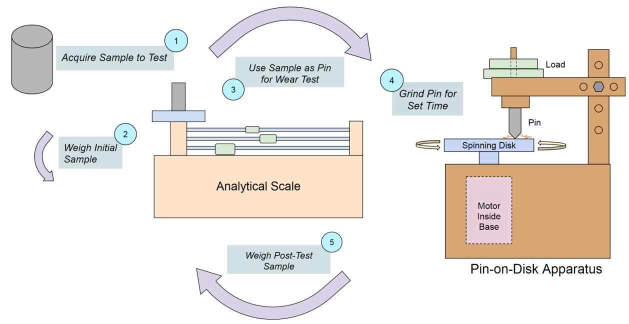
Pin-on-Disk Machines

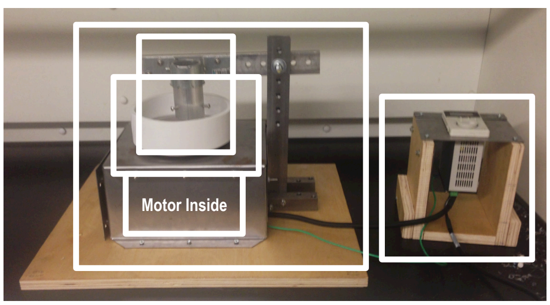
Magnum Engineering TE-165-SPOD Test Rig



Step by Step Use of Pin-on-Disk

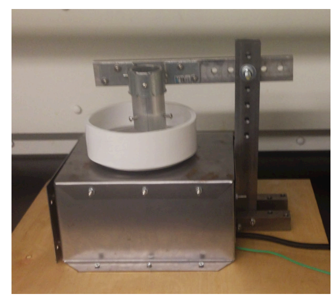


Pin-on-Disk Apparatus Parts



Frame and Supports

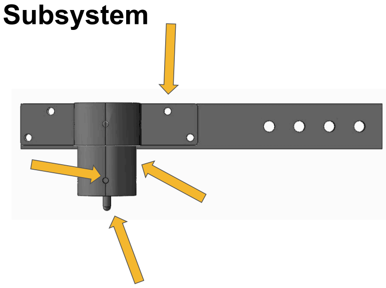
- Sheet metal houses motor
- Arms hold pin over disk at variable heights/distances
  - Pins of various sizes
  - Vertical: mild steel
  - Horizontal: aluminum



Pin-on-disk testing apparatus

Pin Holder Subsystem

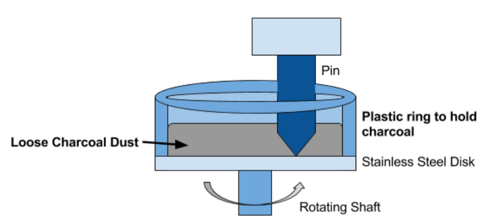
- Fencing strap tie
- Aluminum pipe
- 3 screws
- Sample mounted in epoxy



Pin holder subsystem

Charcoal Placement

- Wide plastic pipe turns disk into cup
- Charcoal rests inside, turns with disk to rub against pin
- Simpler than initial ideas



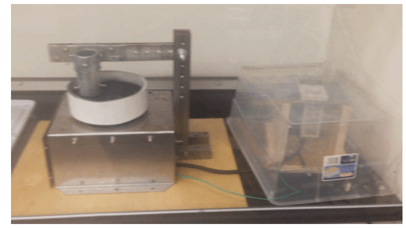
Motor

- Our needs
  - Continuous run-time: +8 hours
  - Rated torque: 18 in-lb
  - Load: 9 lb
  - High dust Protection
  - 60-600 rpm
- Motor: Oriental Motors, Brushless DC
  - Rated Torque: 17.17 in-lb
  - Max Axial load: 33 lb
  - 16-800 rpm
  - Higher dust protection than base model

Oriental Motors Brushless DC Motor Control System

Trial Specifications

- Test
  - 300 rpm
  - 5 hours
  - Ground charcoal
- Pin
  - 1018 Steel
    - Heat treated
  - 1045, 1214, 8620



Pin-on-disk apparatus in operation

Heat Treatment

Carburization

- Higher carbon content strengthens steel
- Carbon in contact with steel soaks into surface (diffusion)
  - Greatly accelerated by high temperature
- Immerse steel in carbon and heat
  - Pack carburization
  - Creates hard surface, leaves interior soft

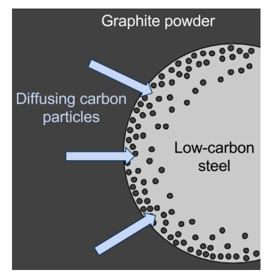


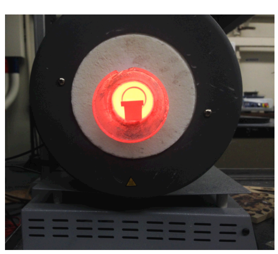
Diagram of carburization process

Carburization

- Case depth: How far carbon has diffused
  - Where carbon halfway between surface & original concentration
- $x = (Dt)^{½}$

Case depth = square root of diffusion constant X time

- D based on materials and temperature
  - x depends on time and temp



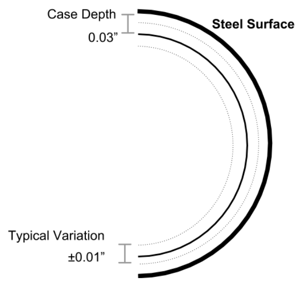
Crucible in furnace at 1000 °C

Quenching

- Post-hardening, to promote development of martensite
- Three Stages
  - Vapor blanket, nucleate boiling, and convection cooling
- Different liquids provide different cooling rates
  - Water: most severe but produces harder surface
  - Oil: less severe quench
- AEST uses water quenching
  - May be causing distortion in auger

Heat Treatment Procedures

- AEST currently carburizing 0.02” case depth
- We carburized at 1000°C for varying durations
- Case depths 0.02” ↔ 0.045”
  - Typical variation of 0.01”



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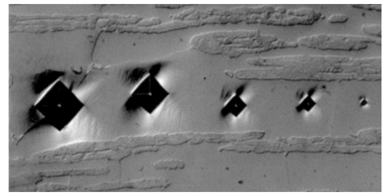
Microhardness Testing

- Diamond tool makes tiny dents in surface for measurement
- Hardness types have different formulas/tools
- Vickers test measures diagonals of square dents

Example of Vickers hardness tests, ASM Handbook, Volume 8



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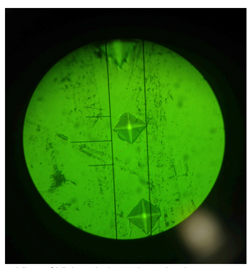
Microhardness Testing

- Smaller samples heat treated with pins
- Test from center to edge to see hardness variation
- Higher hardness expected at edge



View of Vickers indents through microscope

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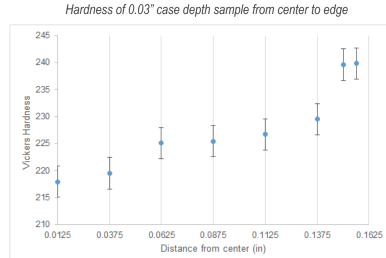
Hardness Verification

Hardness of 0.03” case depth sample from center to edge



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Results

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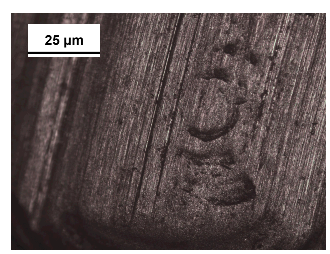
Imaging Results

- Three-body abrasion
  - Pin, disk, charcoal particles
- Pockmarks
  - Likely from construction
  - Repeat trials



Example of pockmarks on heat-treated sample H7, 5x

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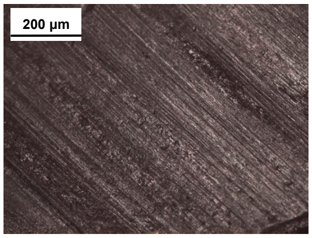
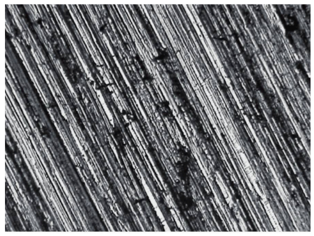
Imaging Results

Comparison of results to 3-body abrasion



Untreated 1018 steel and ground charcoal, 100x



Three-body abrasion, 1020 steel and 60 grit silica, 100x
Via Friction, Wear, and Erosion Atlas

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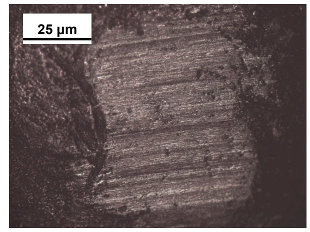
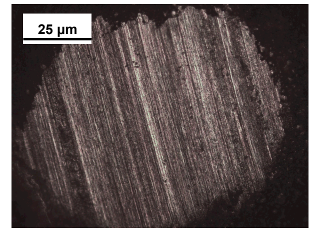
Imaging Results

Comparison of water and oil quenching



0.036 case depth, water quench, 50x



0.036 case depth, oil quench, 50x

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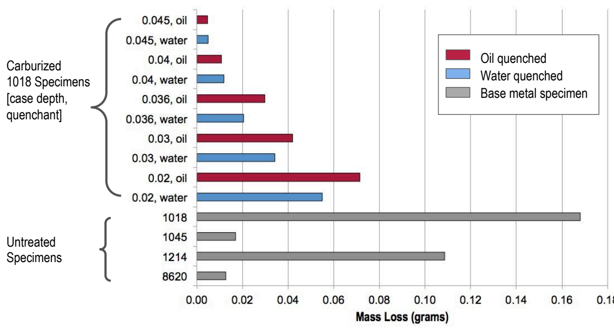
Mass Loss of Pin Specimens in Grams



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Conclusions - Heat Treatment

- **0.04" best blend of improvement/time**
  - 0.045" takes 7 hours – longer than AEST work day
- **Oil better for quenching**
  - Reduces distortion
  - Less residual stress on the sides and ends
  - Thicker case depth = negligible difference from water
    - Higher hardenability
    - Less sensitive to quench

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Conclusions - Material Choice

- **Case depth 0.04" wear resistance similar to 1045, 8620**
  - **Drawbacks of 1045**
    - US: 1045 is 50% more expensive
    - Mild low-carbon steel readily available in Kampala scrap yard, 1045 is $$$
    - Brittle - auger needs soft core
    - Less machinability
  - **Drawbacks of 8620**
    - US: 8620 is 30% more, recycled 8620 not readily available in Kampala
  - **Heat treated 1018 ultimately better**

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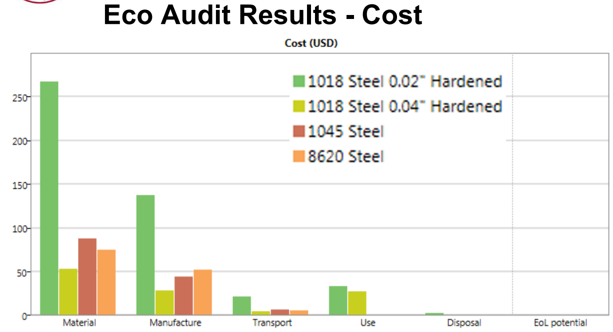
Eco Audit Results - Cost



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Final Suggestion to AEST

- Current
  - Case depth: 0.02”
  - Quenchant: water
- Suggestion
  - Case depth: 0.04”
  - Quenchant: oil (reusable)
    - Investment: quenching oil
    - Budget: motor oil or vegetable oil
  - 80% improvement in wear resistance (0.055g → 0.0108 g)

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Future of the Project

- Experiment
  - Coordinate with MIT D-Labs and EWB team
  - Collect data on in-field wear
- Apparatus
  - Add DAQ / Simulink capabilities to apparatus

AEST employees fabricate auger, 2015

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Summary

- Developed materials science solution to AEST’s short-lived augers
- Made pin-on-disk apparatus with charcoal to simulate/ determine wear
- Heat treated steel to find optimal process
- Concluded 0.04” depth & oil quench best for AEST

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Thank you!

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Supplementary Slides

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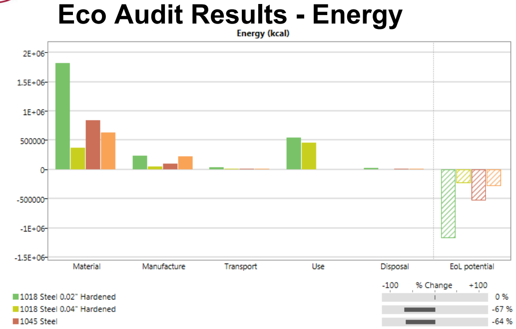
Eco Audit Results - Energy



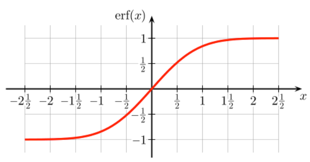
Eco Audit Results - CO_2

Auger Design

- Redesign of the auger is a different project
- Our results are still useful to this future team
  - 1018 is more machinable than 8620 or 1045
- Facilities limitation in Uganda
- Shape would need to provide sufficient pressure

Case Depth Equation

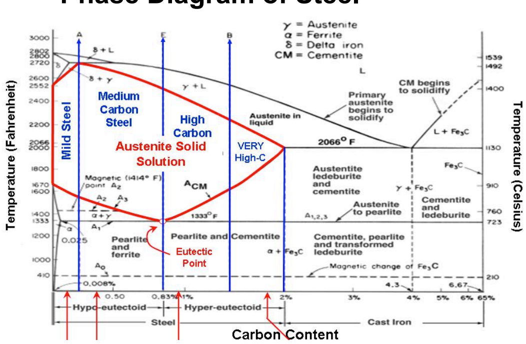
- $C = C_S - (C_S - C_0) * \mathrm{erf}(x/(2*(Dt)^{½}))$
  - C: carbon concentration at depth x
  - C_S: concentration at surface, usually 100%
  - C_0: original concentration, e.g. 18% for 1018
  - t: time spent diffusing
- $D = D_0 * \exp(-Q/(RT))$
  - D_0: material-dependent constant
  - Q: energy to move particles
  - R: ideal gas constant
  - T: temperature



Why carburizing?

- Only heating and quenching 1018 at 1000°C without raising the carbon content through carburization:
  - Sample will form into bainite or pearlite
    - Sample will not form austenite
    - Sample will not form martensite

Phase Diagram of Steel



US price calculations

- Source: OnlineMetals.com
- (3 ft, diameter 1.75") + (12 ft, 0.5") = price
- 1018 = $75.72
- 1045 = $117.13
- 8620 = $105.47

Machinability

- "Ease" with which a metal can be machined
- Determined by the American Iron and Steel Institute (AISI)
- 1112 steel = 100% machinability (arbitrary)
- Less than 100% = more difficult than 1112
- Ratings
  - 1018 = 78%
  - 8620 = 66%
  - 1045 = 57%

Budget

- Funding = $5000
  - $4000 Roelandts Grant, Miller Center for Social Entrepreneurship
  - $1000 from the School of Engineering Undergraduate Programs Senior Design Grant
- Expenditures = $3300
  - Apparatus = $1000
  - Analytical Scale = $1400
  - Testing Supplies = $900

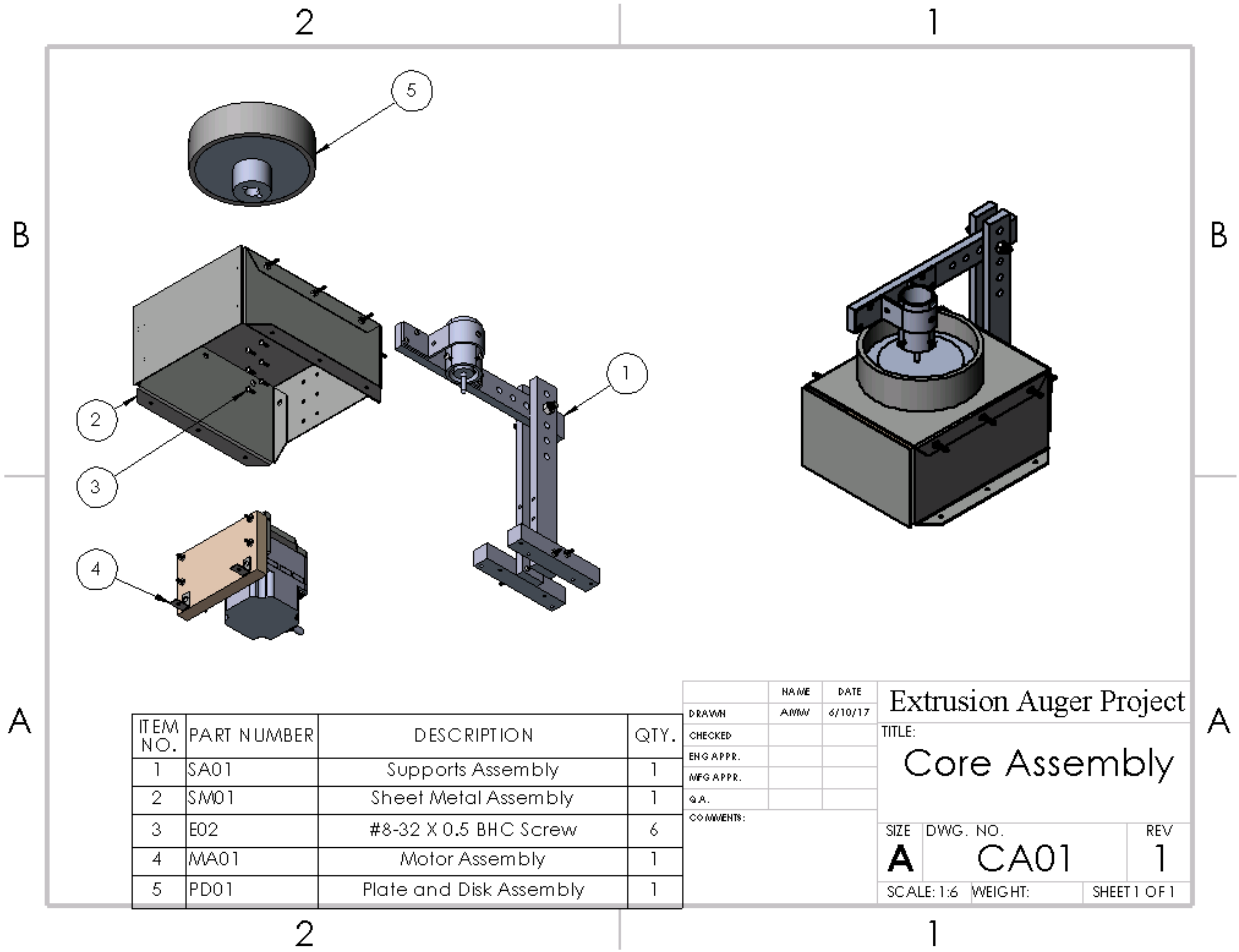
Video of Current Quenching Process

Appendix I: Parts Drawings

Table I 1 – Bill of Materials

Assembly + #	*Parts*	#
Extras	0.375 in hex screw	E01
E	0.5 in hex screw	E02
	0.75 in hex screw	E03
	1.0 in hex screw	E04
	1.5 in hex screw	E05
	2.0 in hex screw	E06
	2.5 in hex screw	E07
	0.5 in wood screw	E08
	1.25 in wood screw	E09
	1.5 in wood screw	E10
	2 in wood screw	E11
	#8-32 hex nut	E12
	0.375 in hex nut	E13
	0.375 in lock washer	E14
	0.5 in round magnet	E15
	Corner bracket	E16
Driver	Motor Driver	D01
DA01	Driver Floor	W01
	Right Driver Wall	W02
	Left Driver Wall	W03
	Driver Foot	W04
	Driver Sheet Metal Side	D02
	Driver Sheet Metal Narrow	D03
	Driver Sheet Metal Wide	D04
Motor	Motor	M01
MA01	Motor Bracket	M02
	Motor Shaft Key	M03
	Wood for Motor	W05
Plate and Disk	Supporting Plate	P01
PD01	Plate Plug	P02
	Cup Ring	P03
	Disk	P04
	Interface Shaft	P05

Assembly + #	*Parts*	*#*
Horizontal	Horizontal Arm	H01
HA01	Modified Simpson Strong-Tie	H02
	Sample Holder	H03
	Pin (Epoxy-Mounted)	H04
Supports	Left Foot	V01
SA01	Right Foot	V02
	Vertical Arm	V03
	Pivot Pin	V04
Sheet Metal	Sheet Metal Back	S01
SM01	Sheet Metal Left	S02
	Sheet Metal Right	S03
	Sheet Metal Front	S04
	Sheet Metal Top	S05
Core		
CA01		
Full Pin-on-Disk	Wood Platform	W06
FA01		
Horizontal	Horizontal Arm	H01
HA01	Modified Simpson Strong-Tie	H02
	Sample Holder	H03
	Pin (Epoxy-Mounted)	H04
Supports	Left Foot	V01
SA01	Right Foot	V02
	Vertical Arm	V03
	Pivot Pin	V04
Sheet Metal	Sheet Metal Back	S01
SM01	Sheet Metal Left	S02
	Sheet Metal Right	S03
	Sheet Metal Front	S04
	Sheet Metal Top	S05
Core		
CA01		
Full Pin-on-Disk	Wood Platform	W06
FA01		
Horizontal	Horizontal Arm	H01
HA01	Modified Simpson Strong-Tie	H02



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	SA01	Supports Assembly	1
2	SM01	Sheet Metal Assembly	1
3	E02	#8-32 X 0.5 BHC Screw	6
4	MA01	Motor Assembly	1
5	PD01	Plate and Disk Assembly	1

Figure I 1 – Assembly drawing CA01.

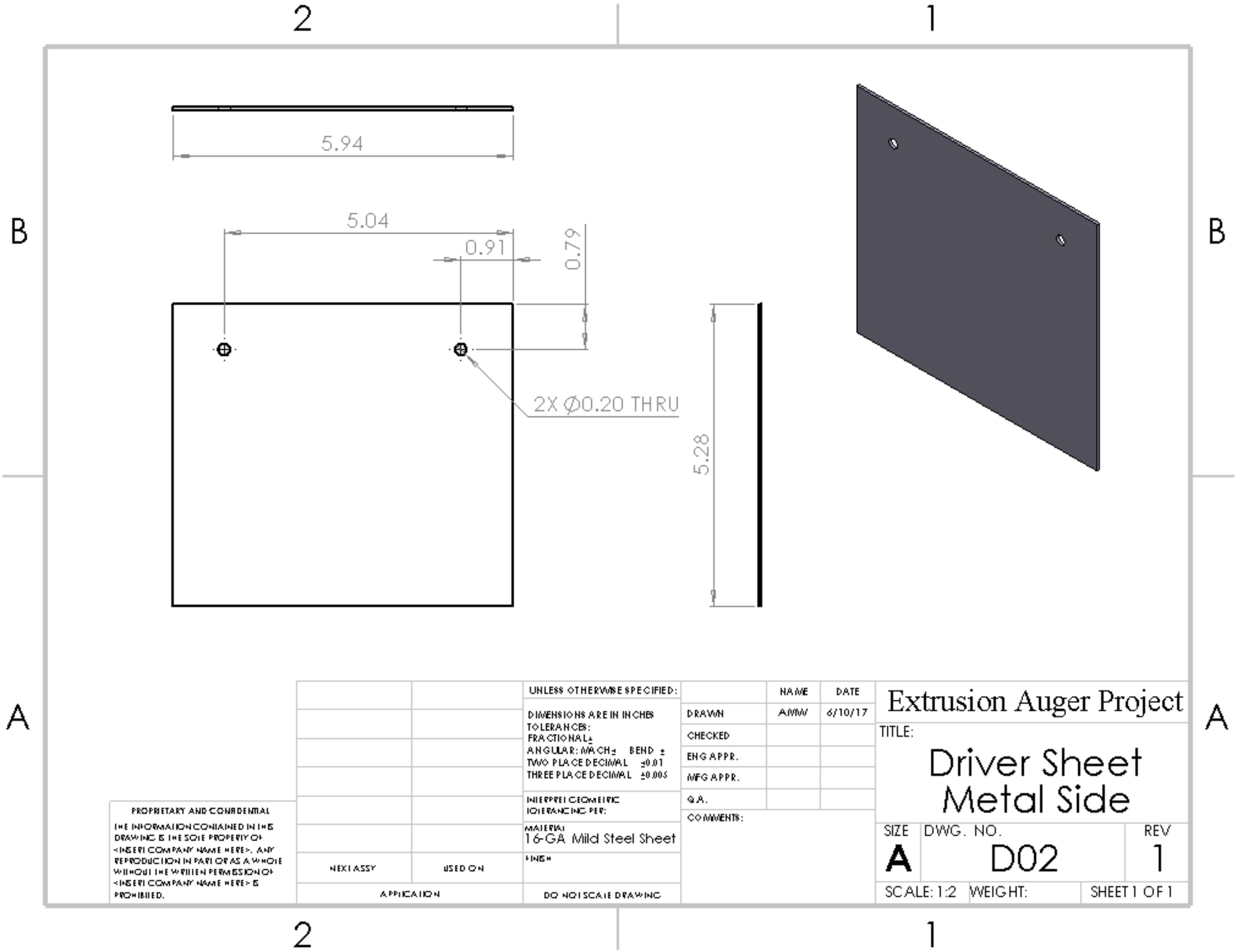


Figure I 2 – Part drawing D02.

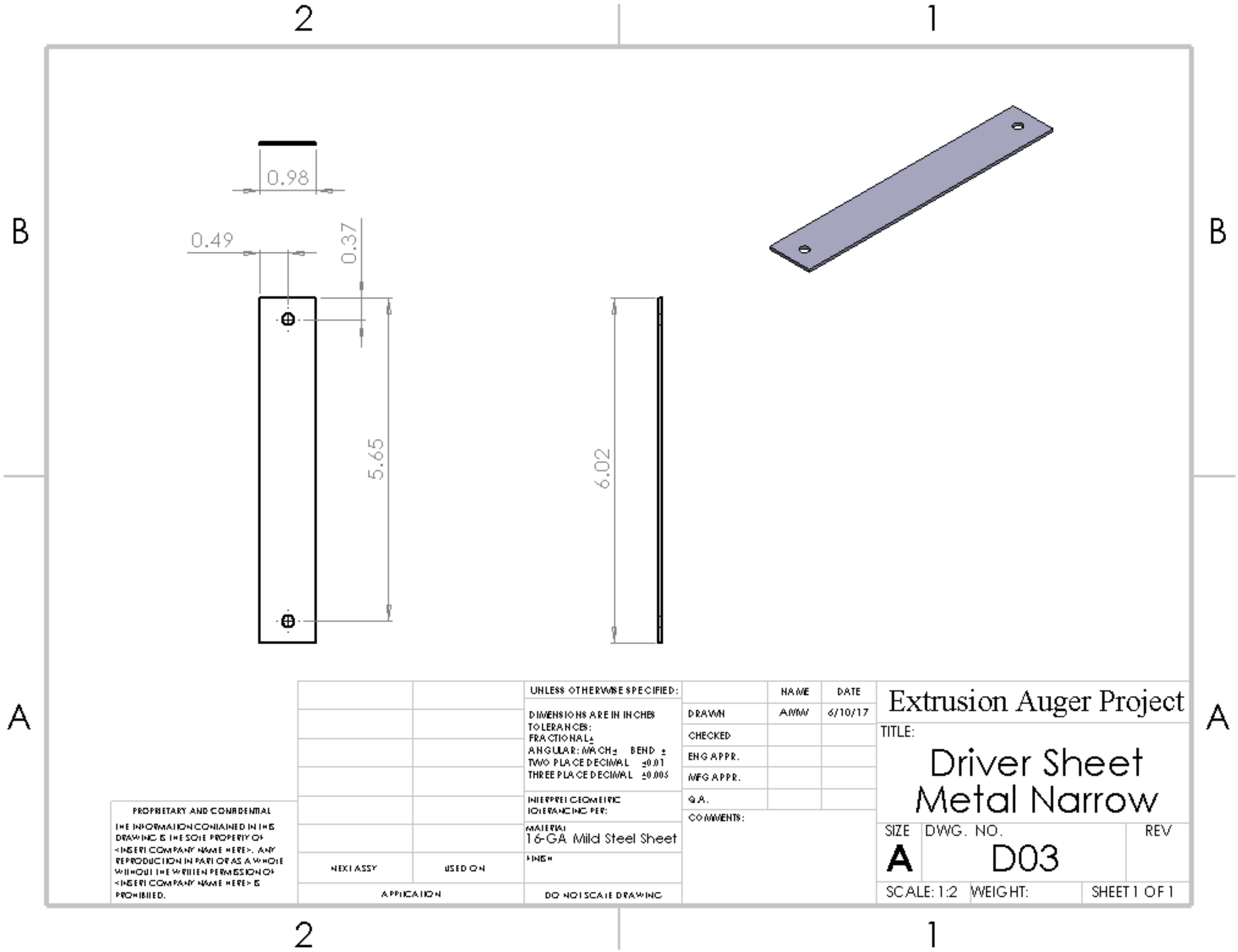


Figure I 3 – Part drawing D03.

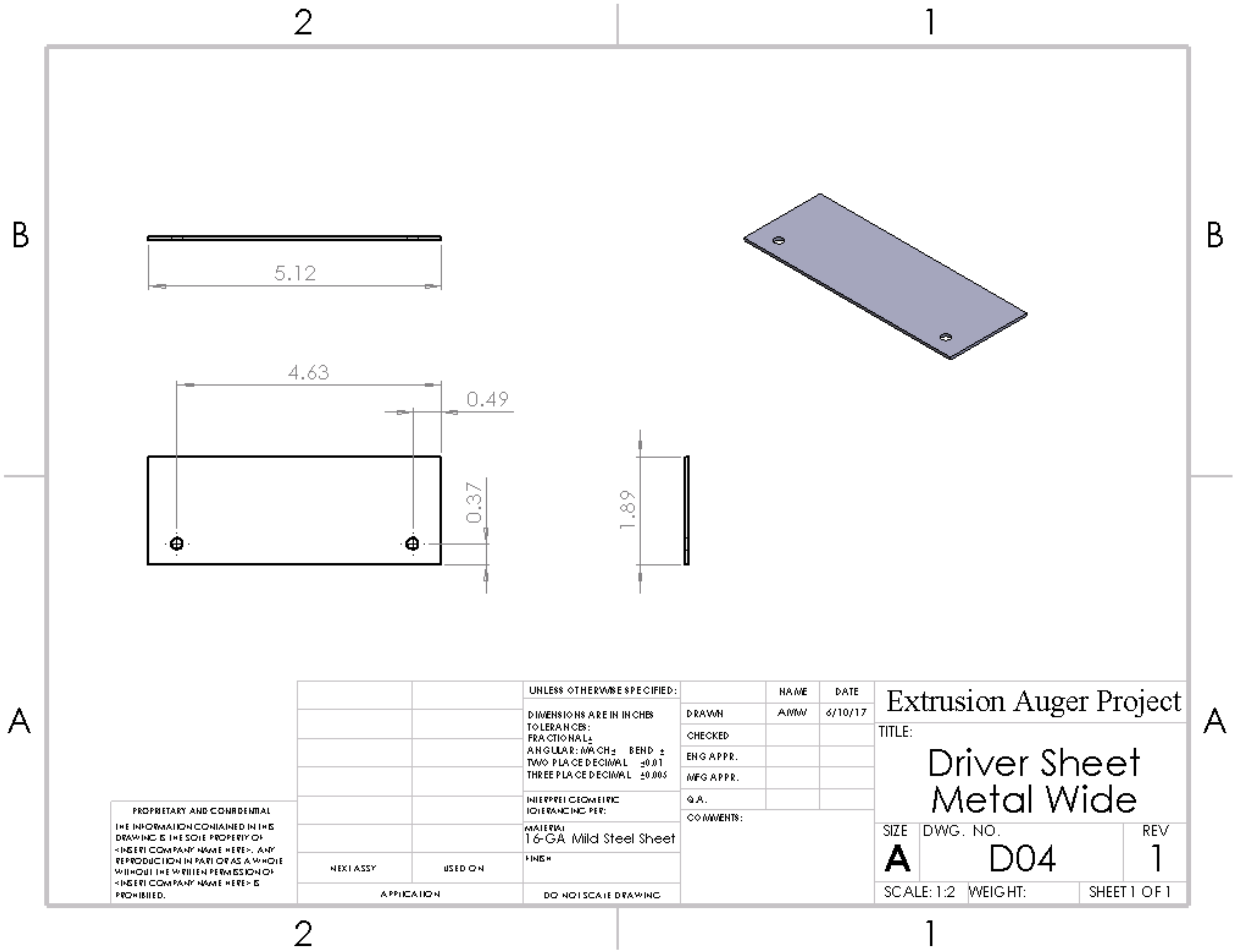
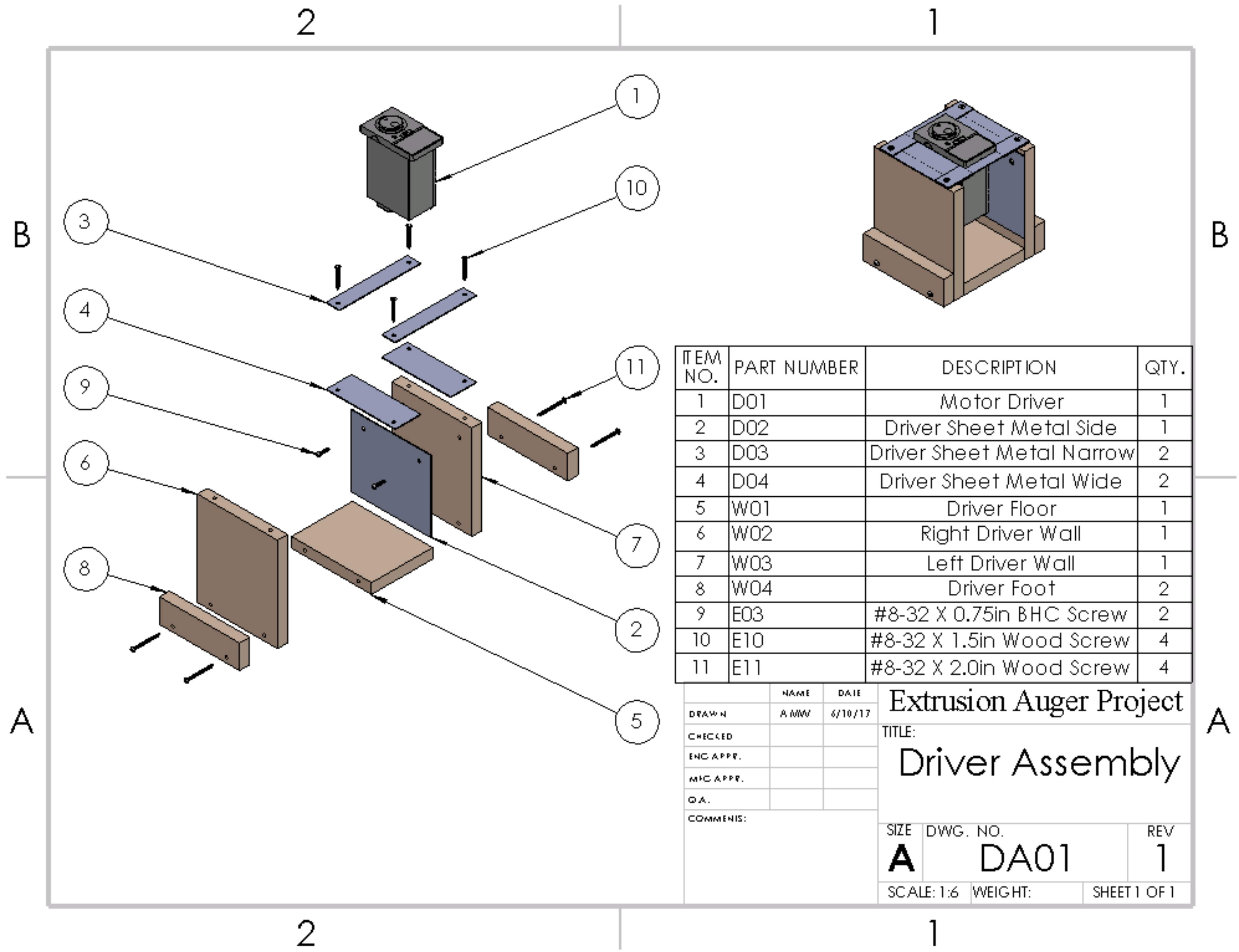
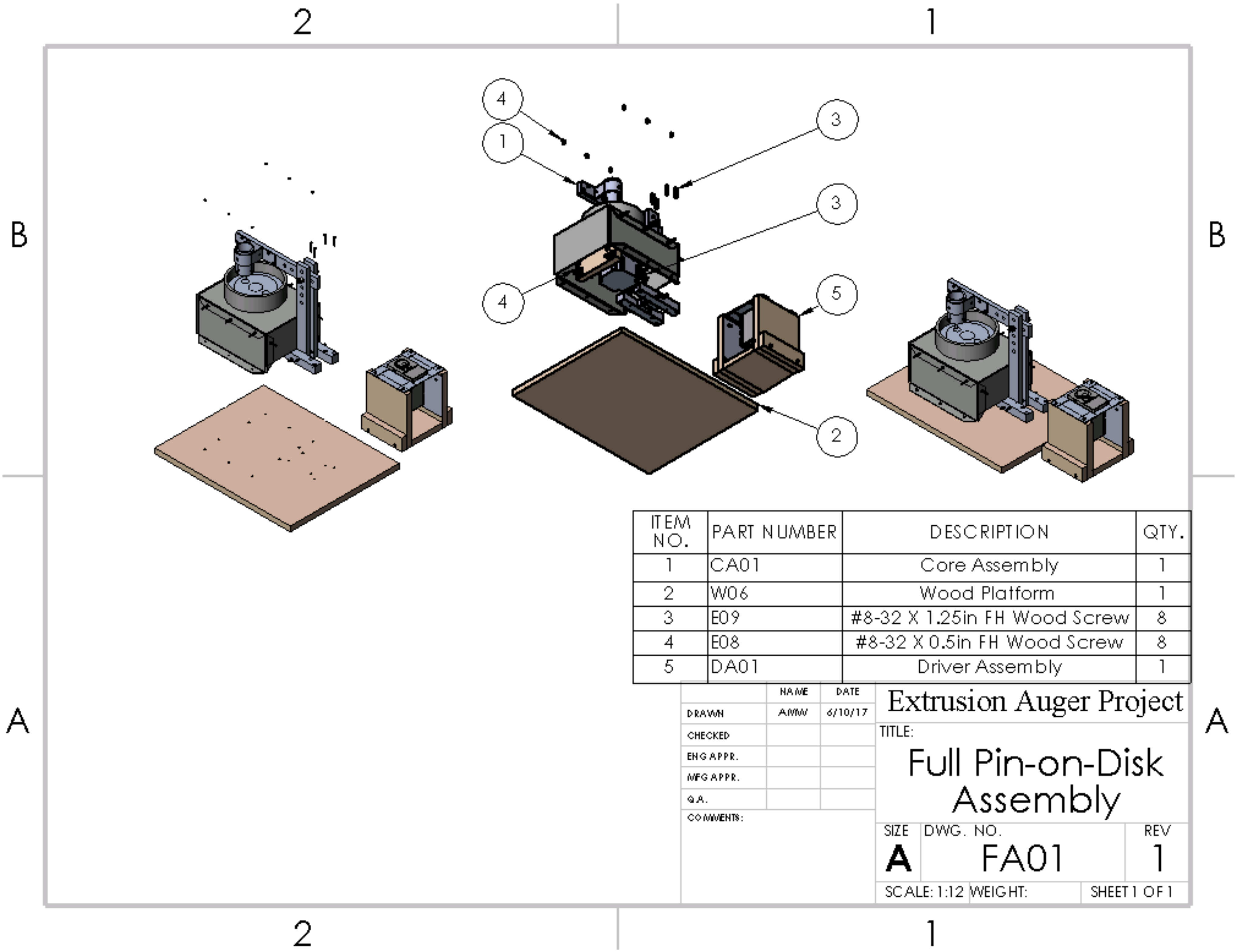


Figure I 4 – Part drawing D04.



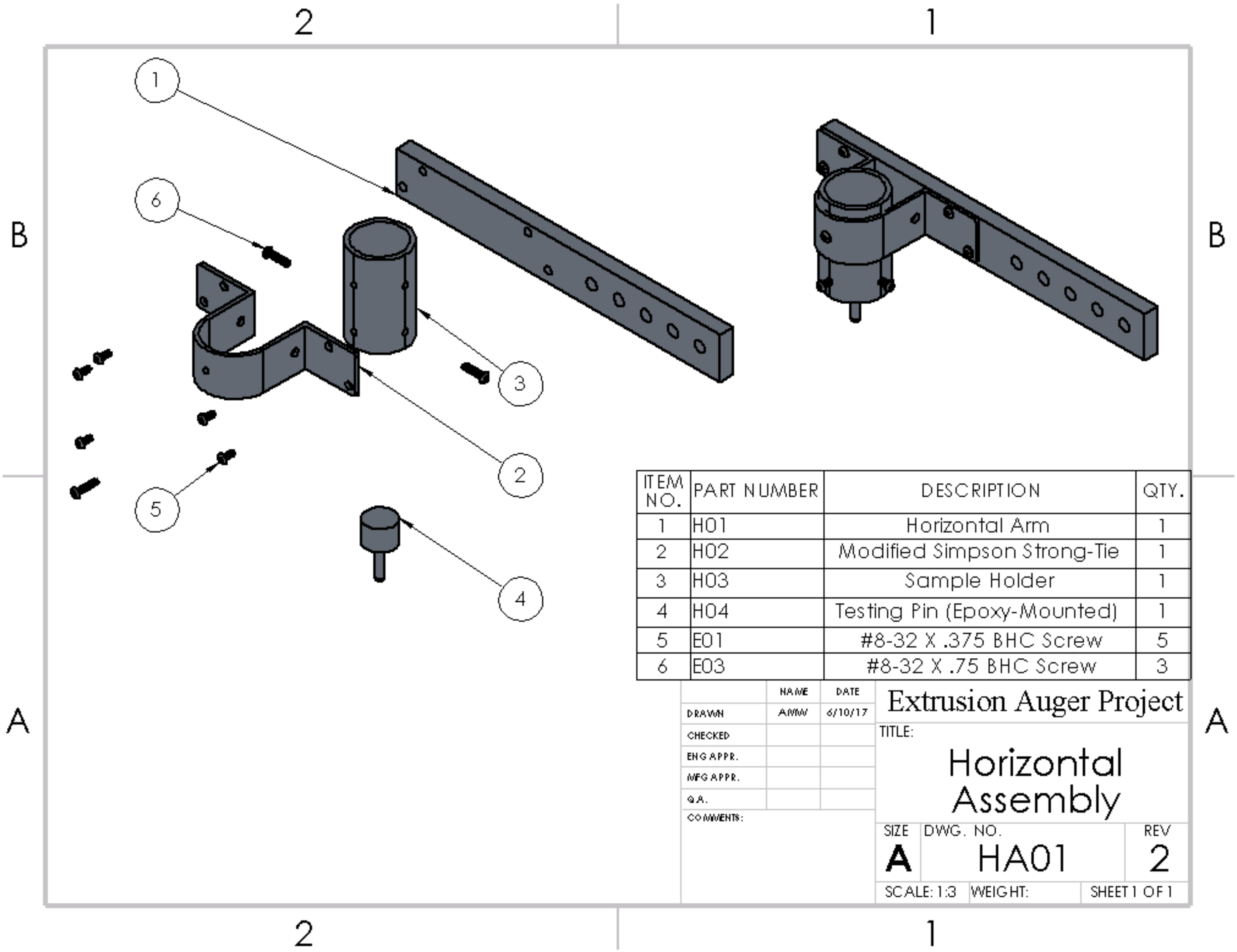
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	D01	Motor Driver	1
2	D02	Driver Sheet Metal Side	1
3	D03	Driver Sheet Metal Narrow	2
4	D04	Driver Sheet Metal Wide	2
5	W01	Driver Floor	1
6	W02	Right Driver Wall	1
7	W03	Left Driver Wall	1
8	W04	Driver Foot	2
9	E03	#8-32 X 0.75in BHC Screw	2
10	E10	#8-32 X 1.5in Wood Screw	4
11	E11	#8-32 X 2.0in Wood Screw	4

Figure I 5 – Assembly drawing DA01.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	CA01	Core Assembly	1
2	W06	Wood Platform	1
3	E09	#8-32 X 1.25in FH Wood Screw	8
4	E08	#8-32 X 0.5in FH Wood Screw	8
5	DA01	Driver Assembly	1

Figure I 6 – Assembly drawing FA01.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	H01	Horizontal Arm	1
2	H02	Modified Simpson Strong-Tie	1
3	H03	Sample Holder	1
4	H04	Testing Pin (Epoxy-Mounted)	1
5	E01	#8-32 X .375 BHC Screw	5
6	E03	#8-32 X .75 BHC Screw	3

Figure I 7 – Assembly drawing HA01.

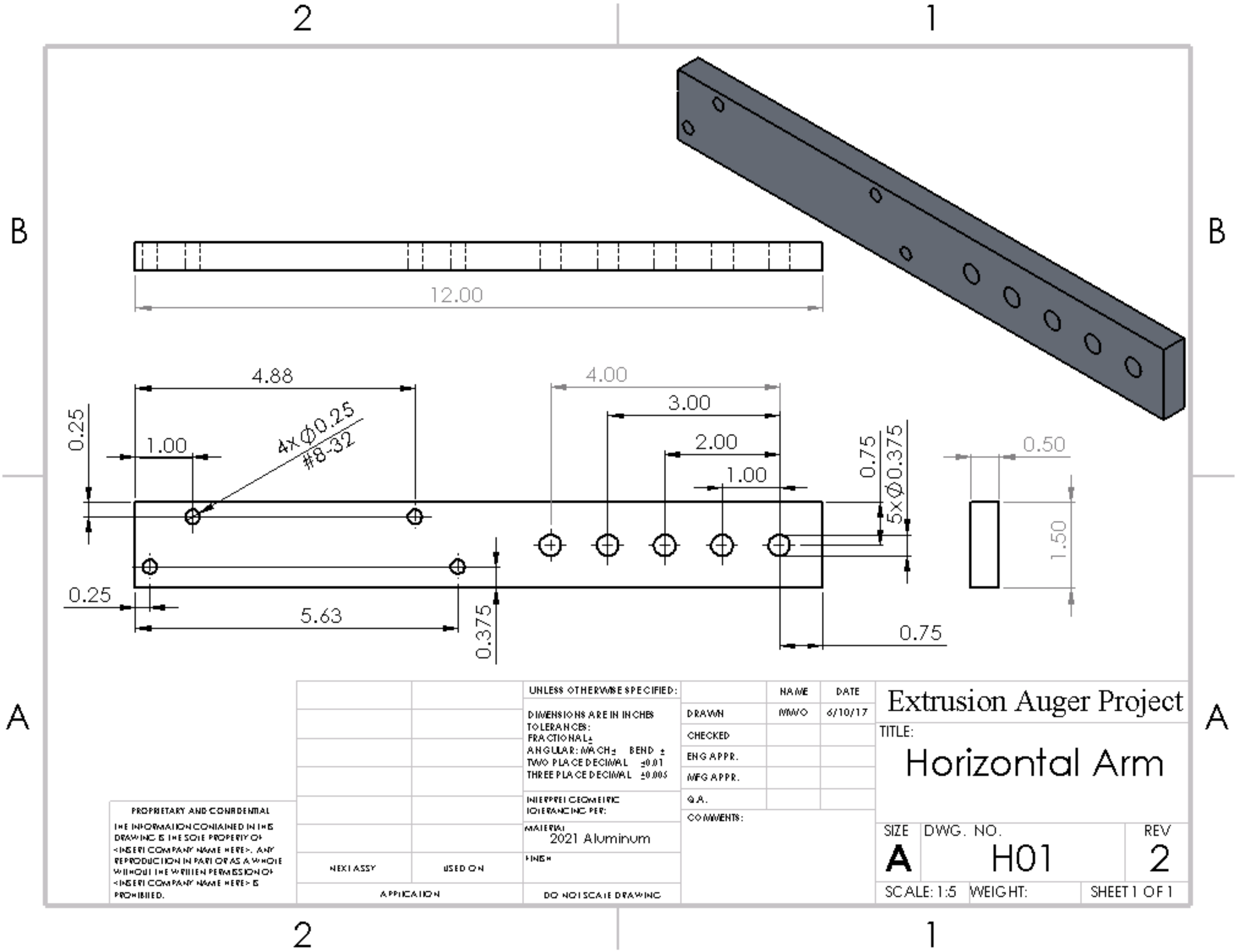


Figure I 8 – Part drawing H01.

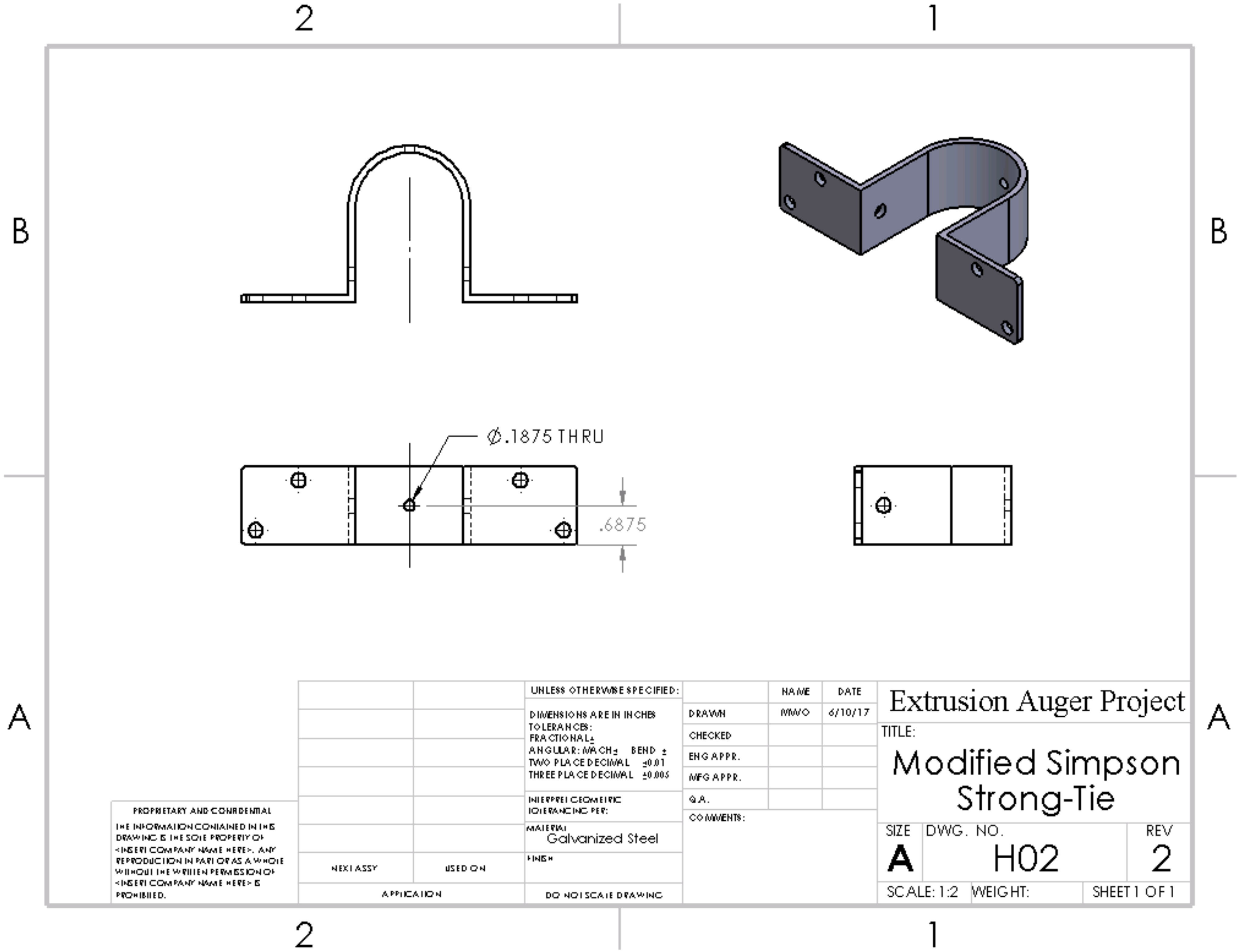


Figure I 9 – Part drawing H02.

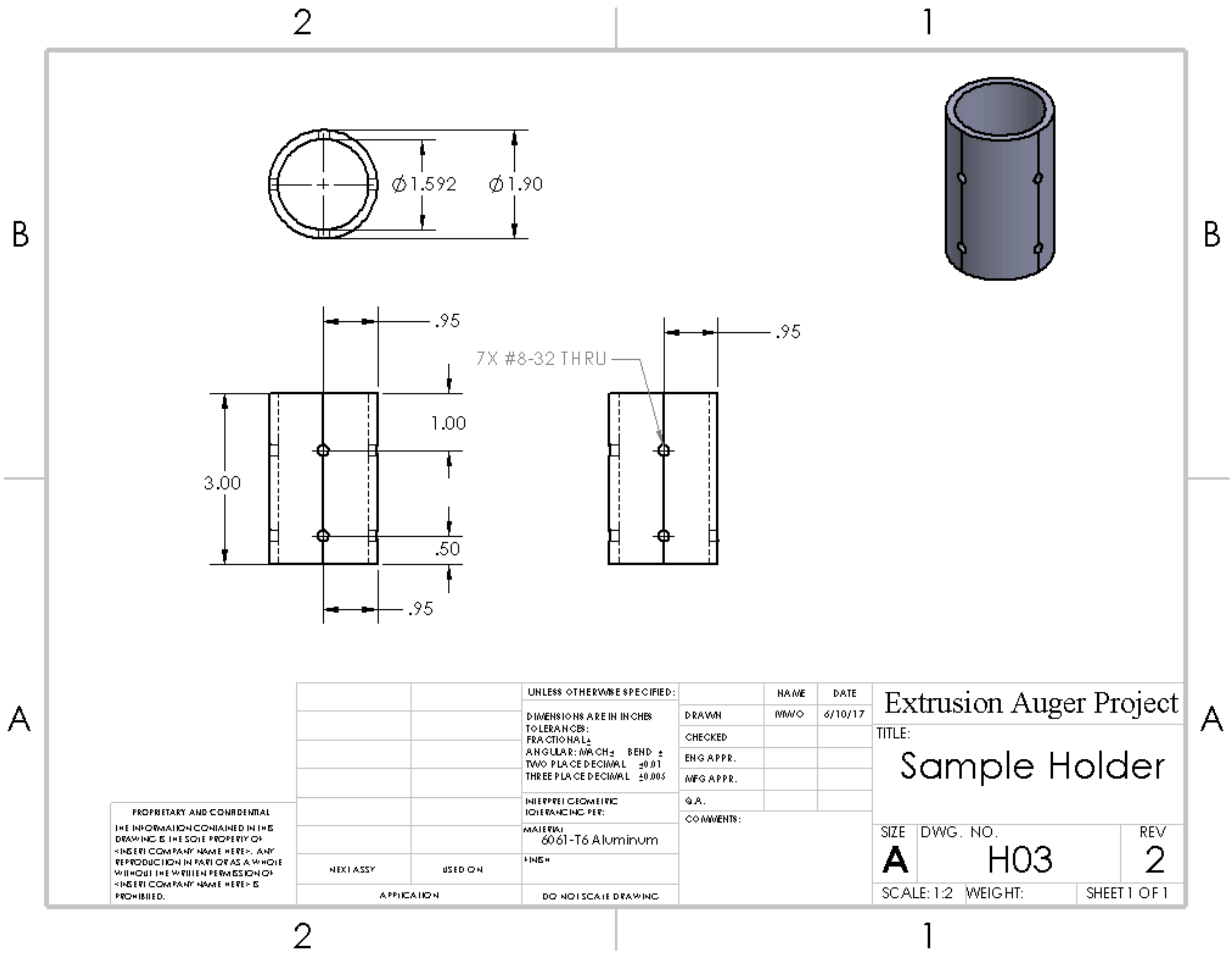
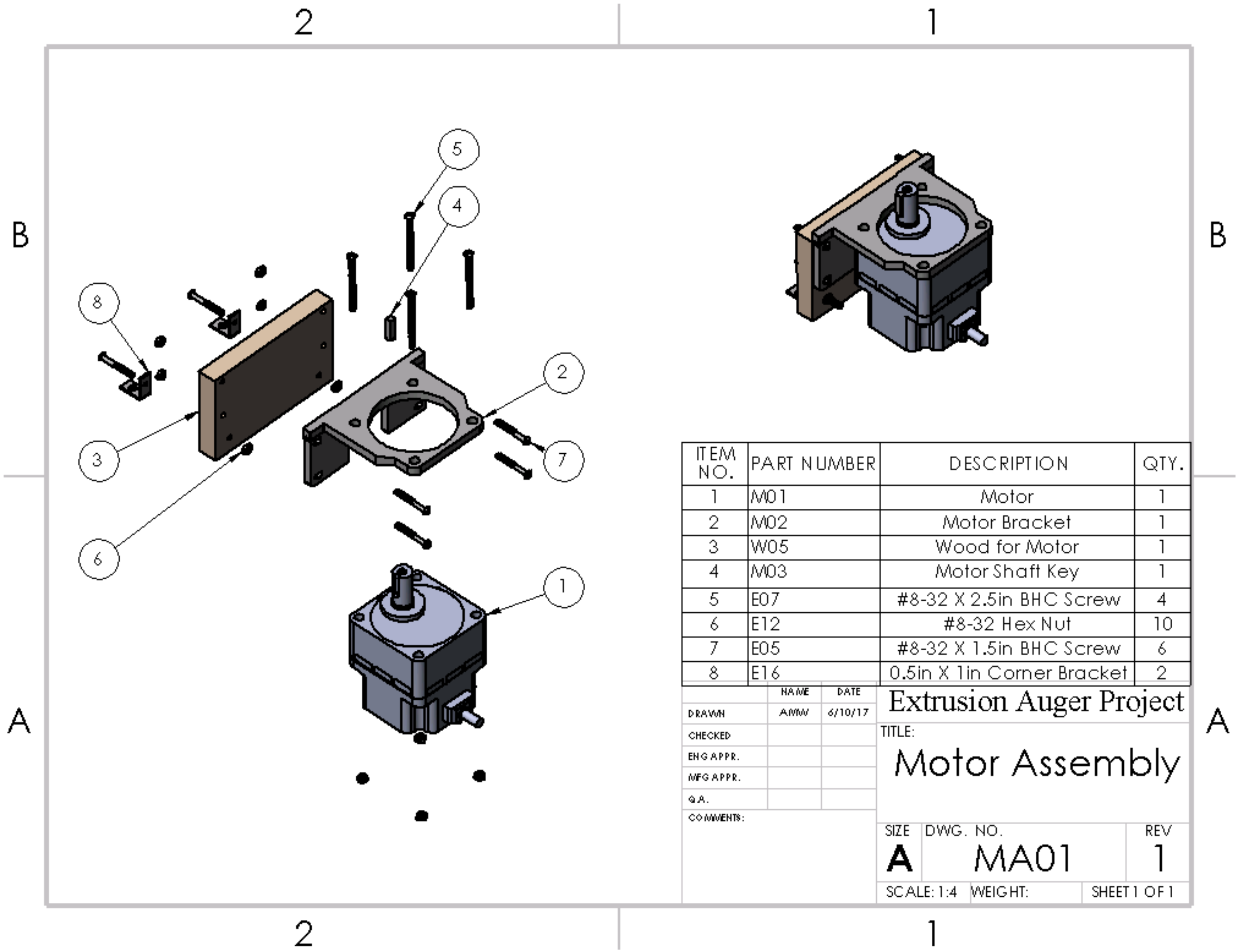


Figure I 10 – Part drawing H03.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	M01	Motor	1
2	M02	Motor Bracket	1
3	W05	Wood for Motor	1
4	M03	Motor Shaft Key	1
5	E07	#8-32 X 2.5in BHC Screw	4
6	E12	#8-32 Hex Nut	10
7	E05	#8-32 X 1.5in BHC Screw	6
8	E16	0.5in X 1in Corner Bracket	2

Figure I 11 – Assembly drawing MA01.

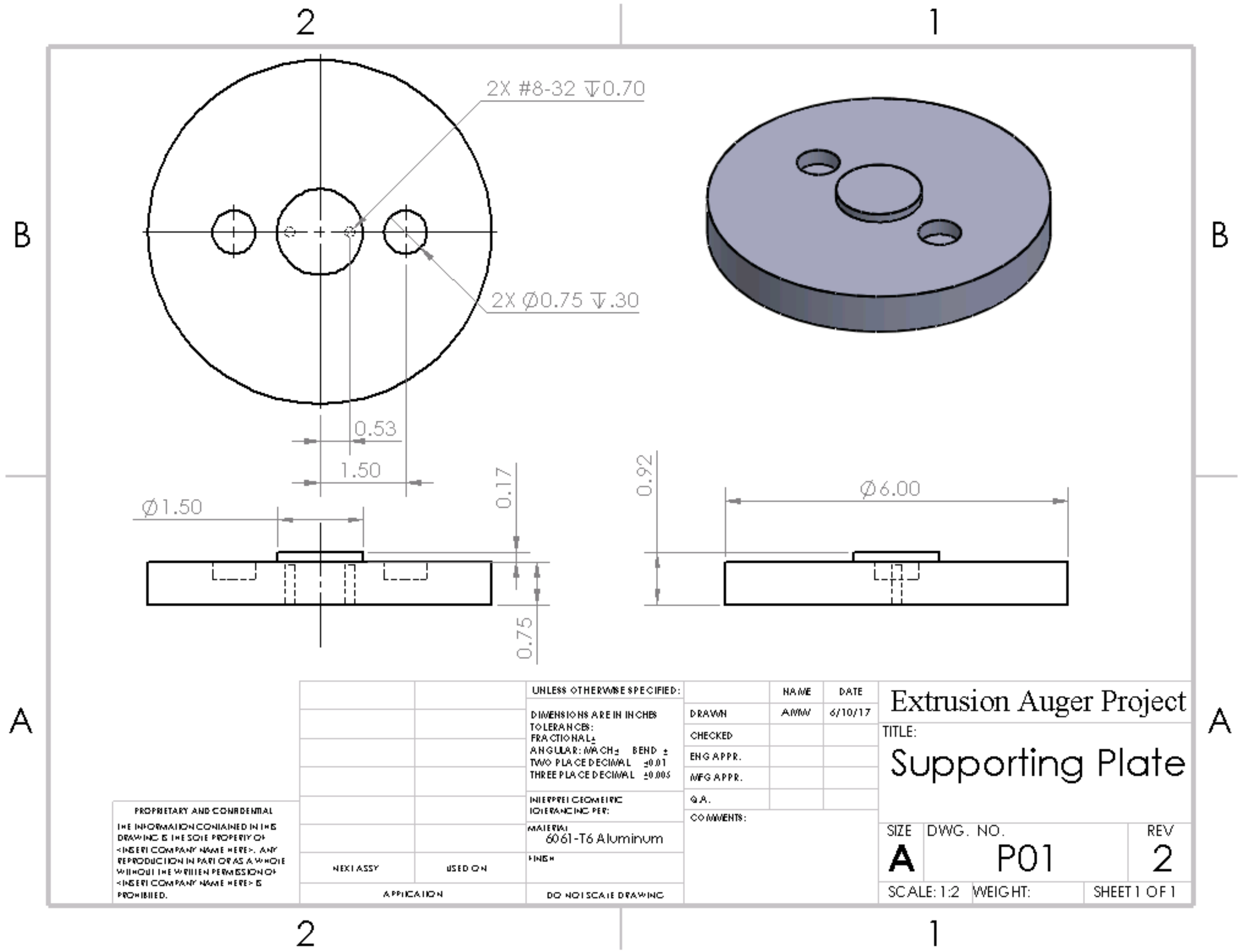


Figure I 12 – Part drawing P01.

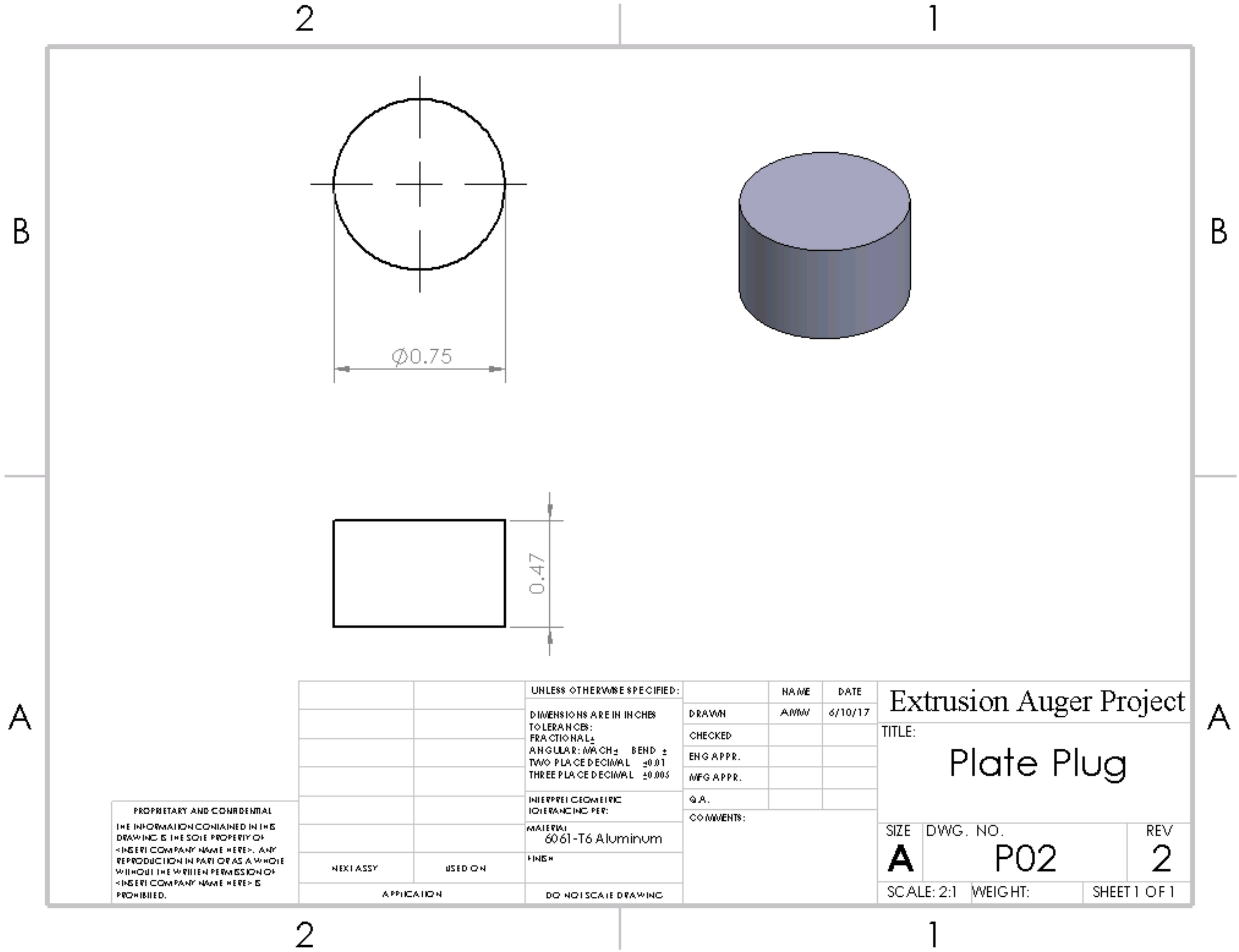


Figure I 13 – Part drawing P02.

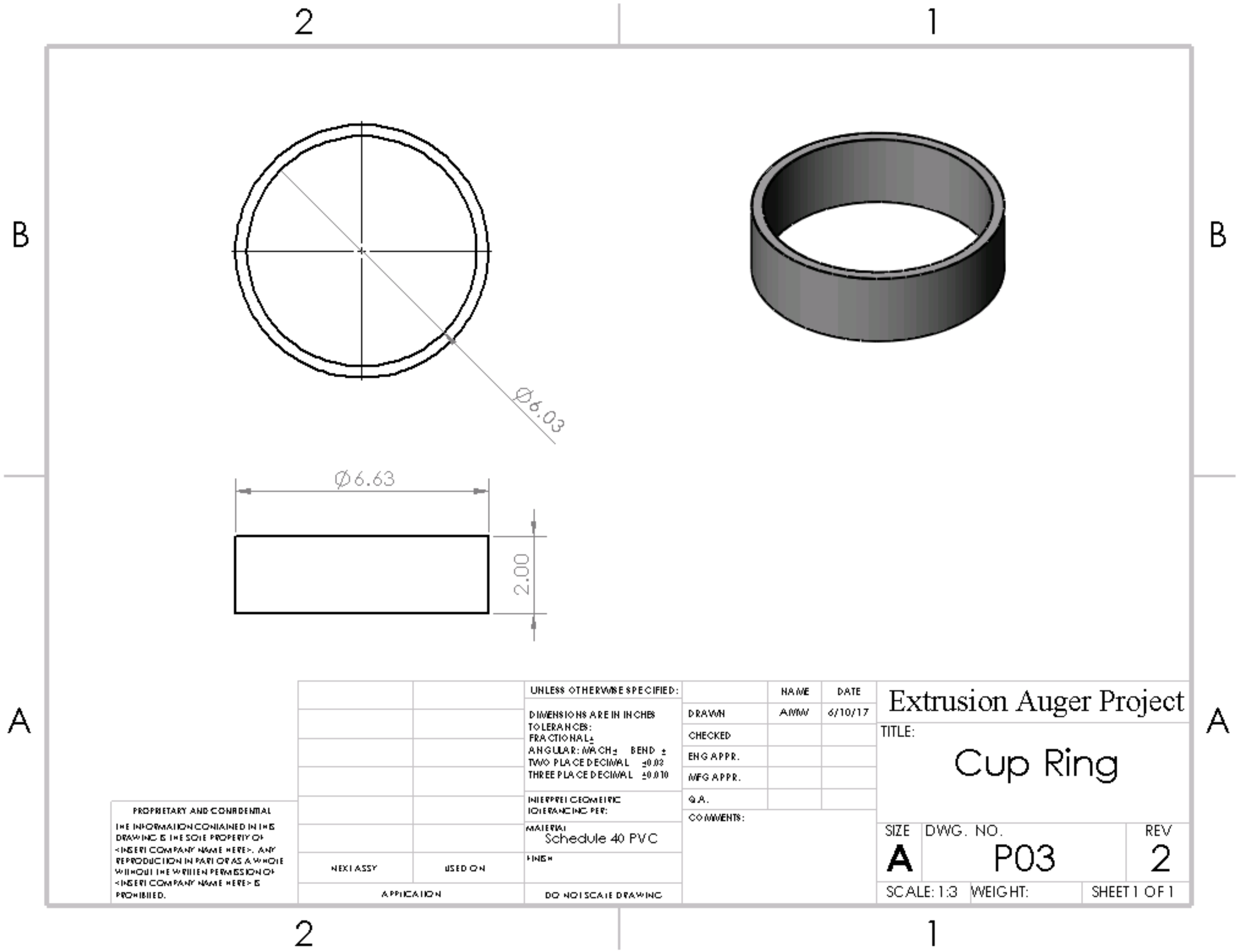


Figure I 14 – Part drawing P03.

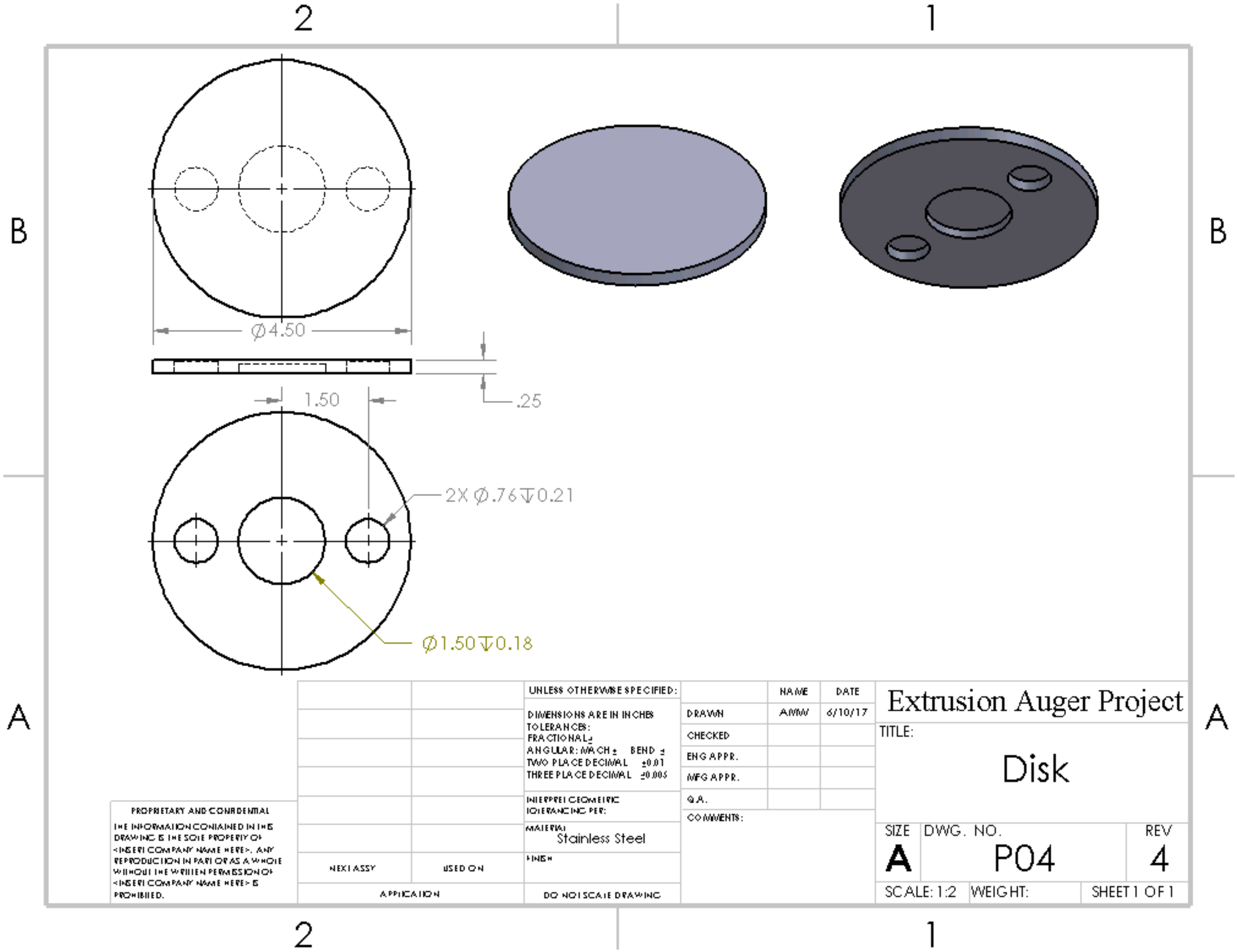


Figure I 15 – Part drawing P04.

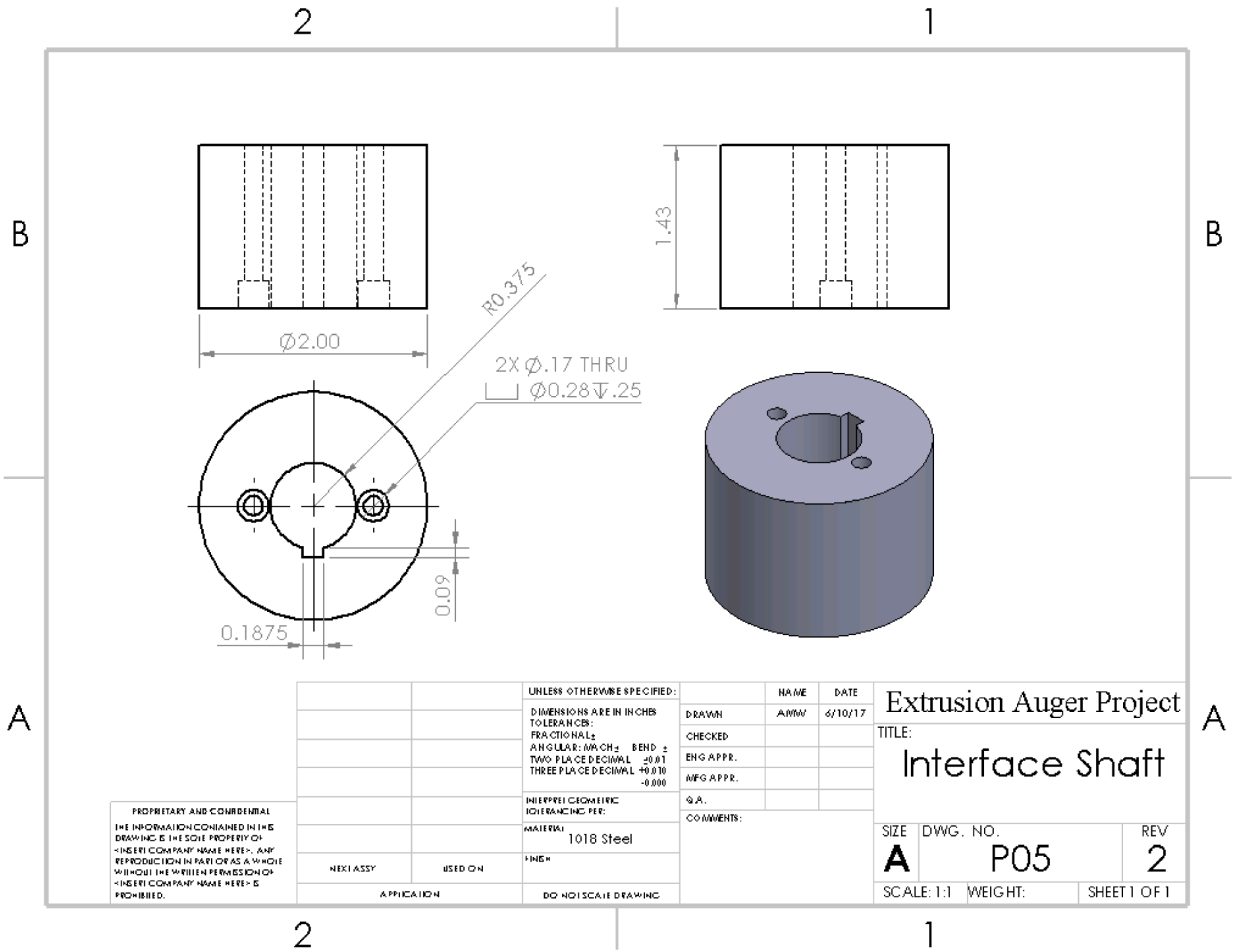
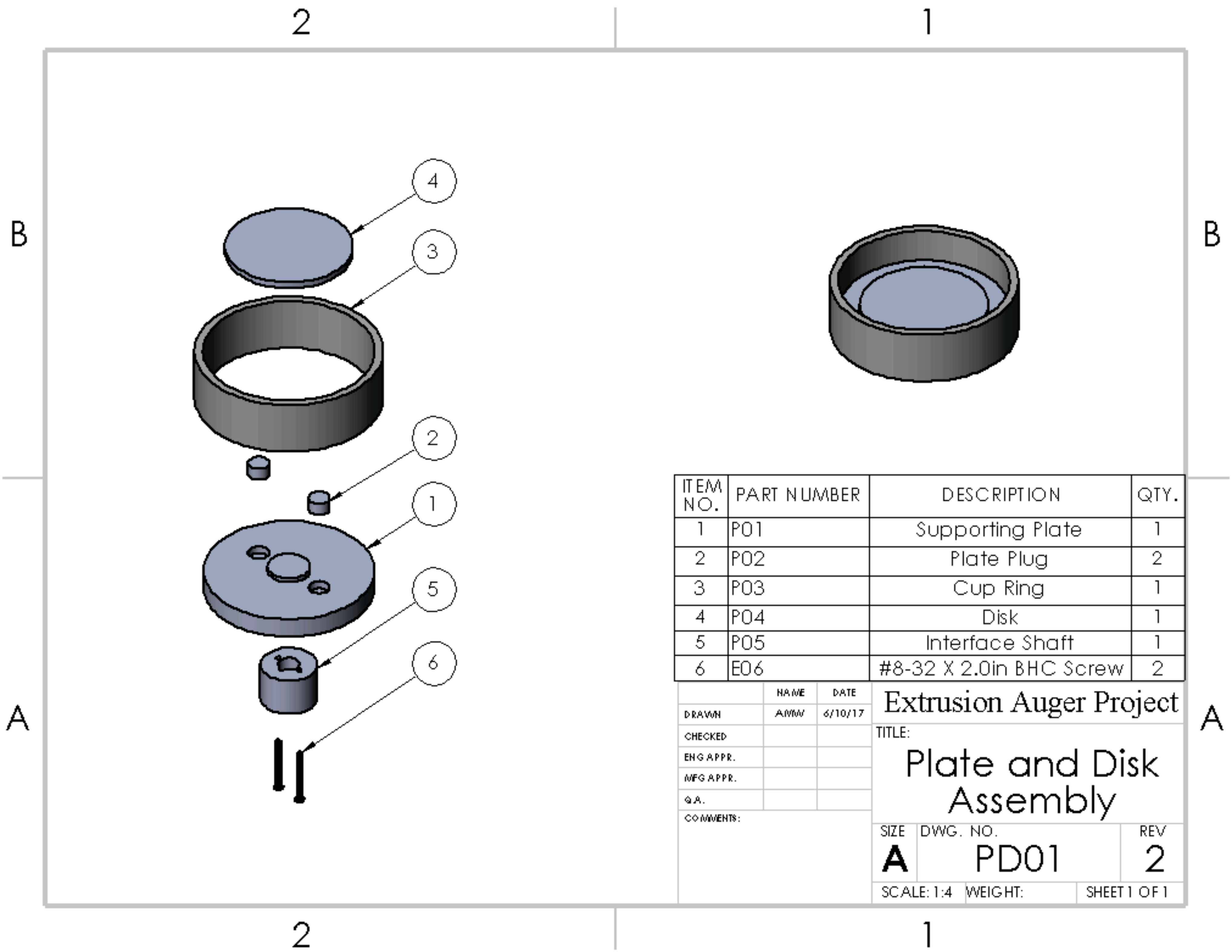


Figure I 16 – Part drawing P05.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P01	Supporting Plate	1
2	P02	Plate Plug	2
3	P03	Cup Ring	1
4	P04	Disk	1
5	P05	Interface Shaft	1
6	E06	#8-32 X 2.0in BHC Screw	2

Figure I 17 – Assembly drawing PD01.

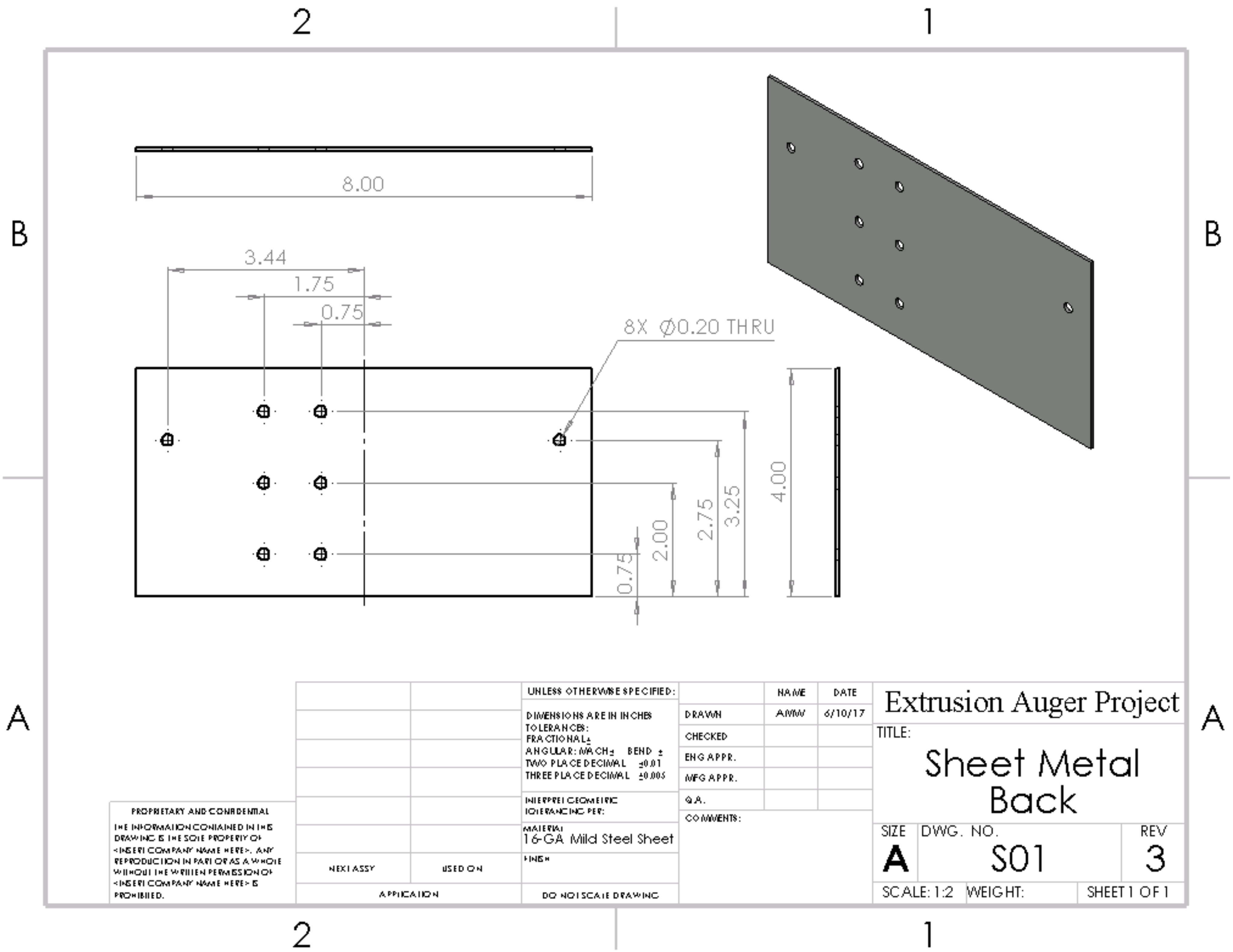


Figure I 18 – Part drawing S01

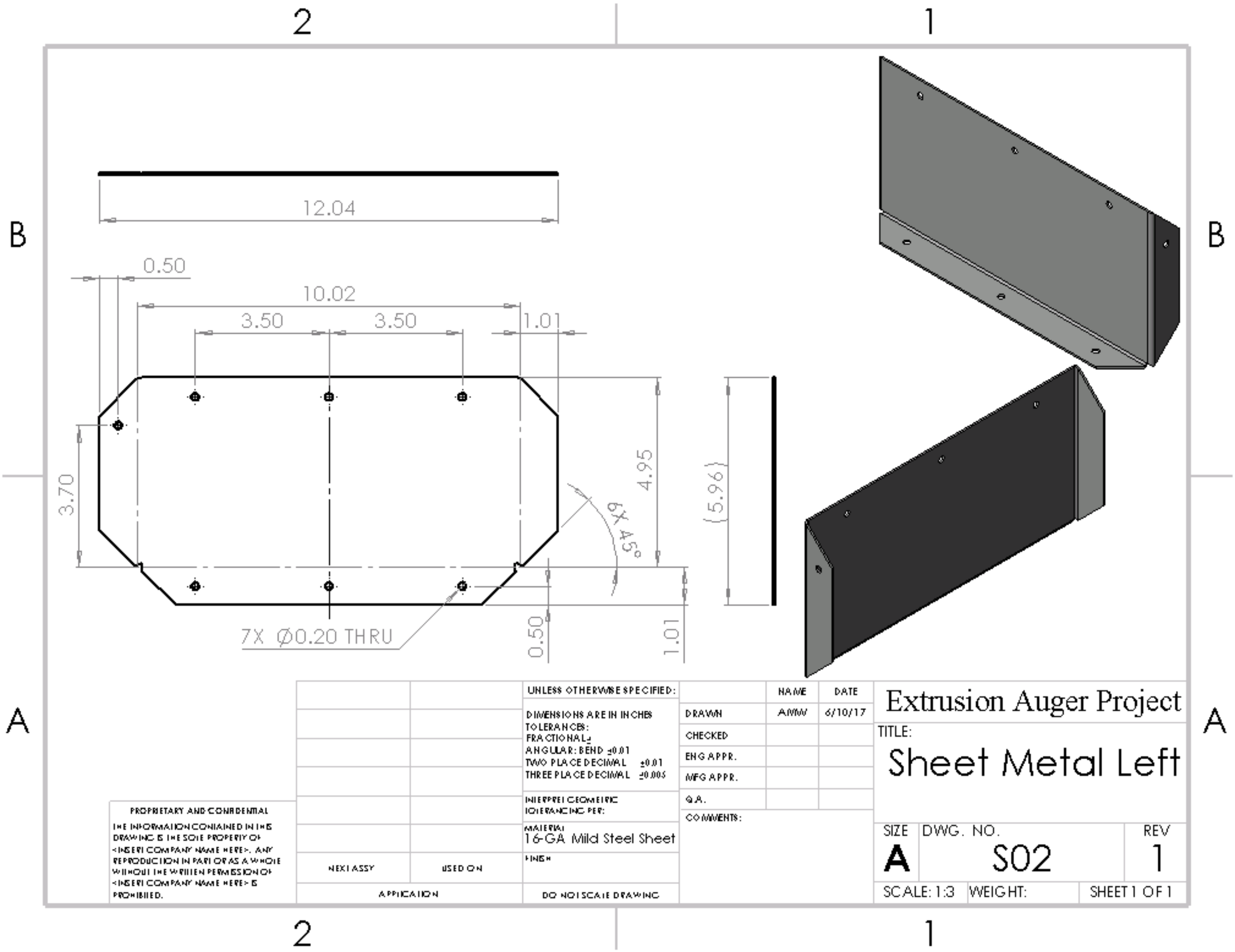


Figure I 19 – Part drawing S02.

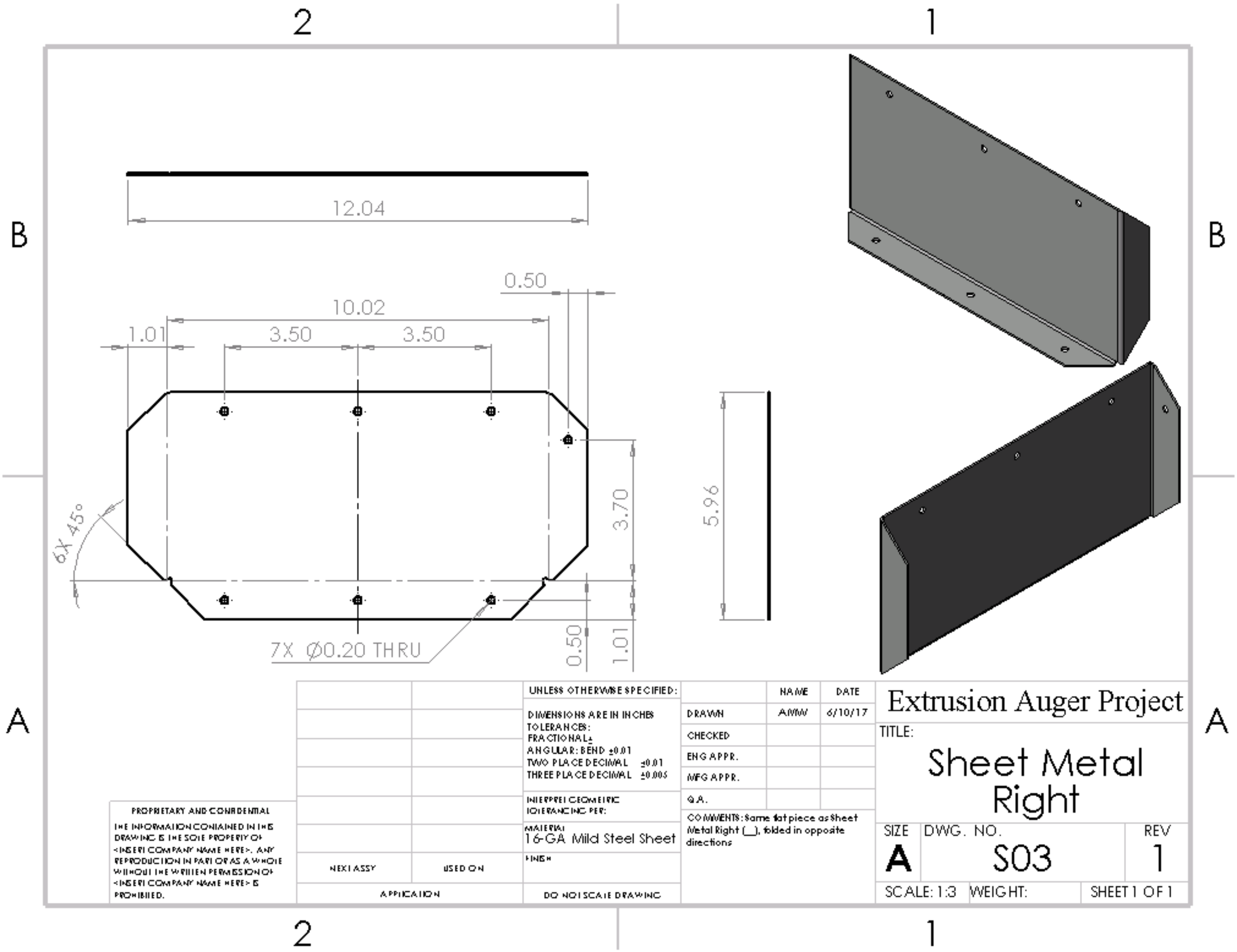


Figure I 20 – Part drawing S03.

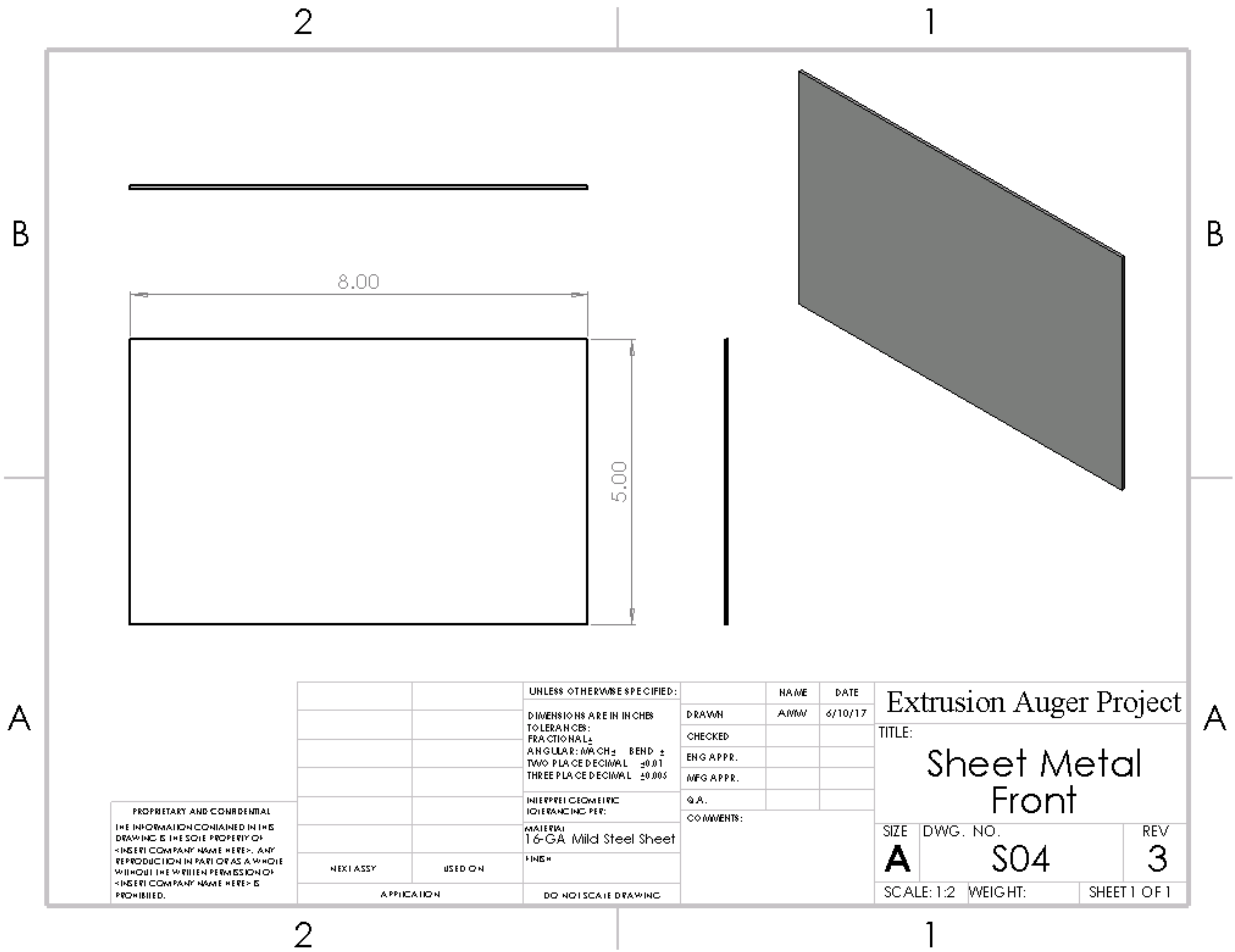


Figure I 21 – Part drawing S04.

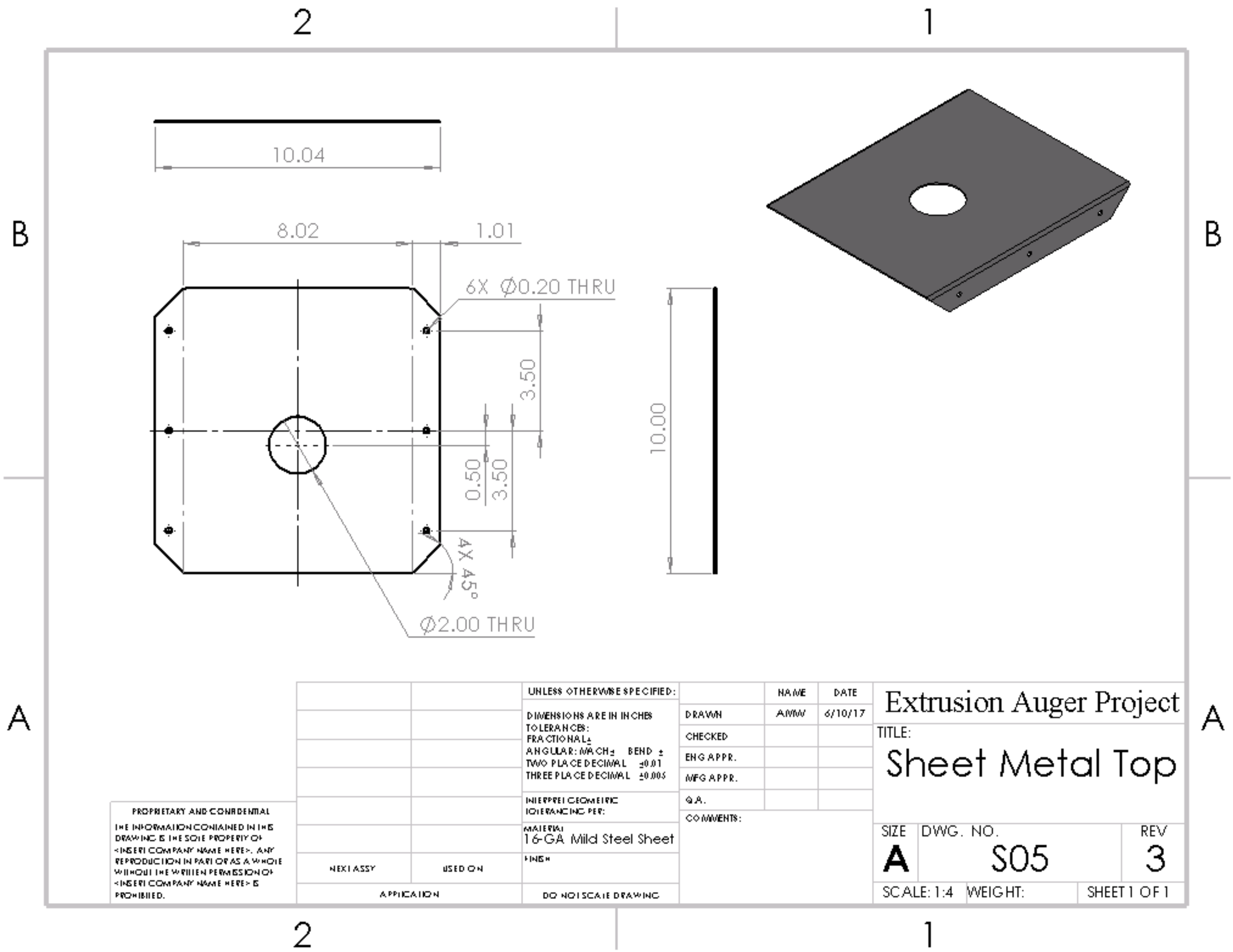
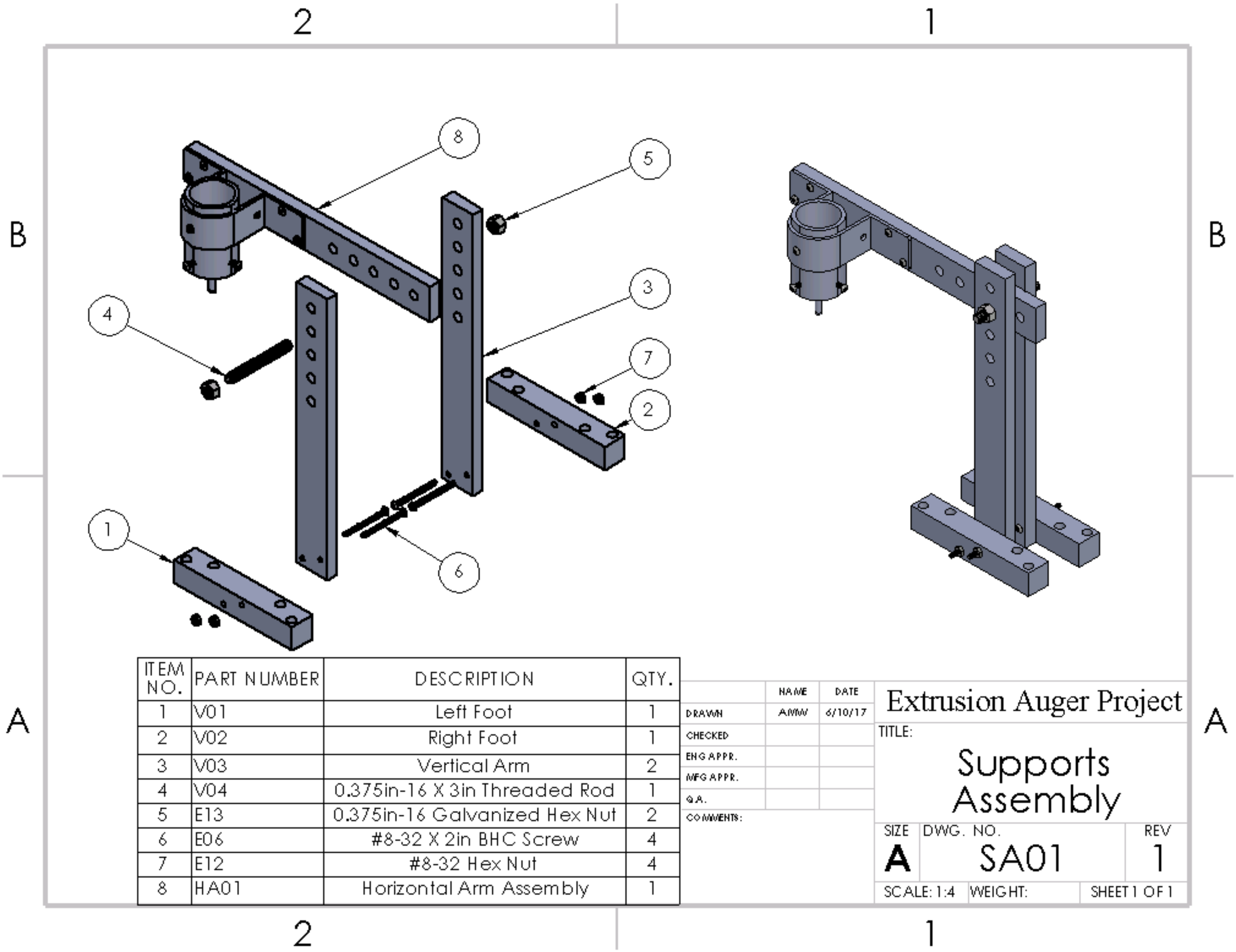
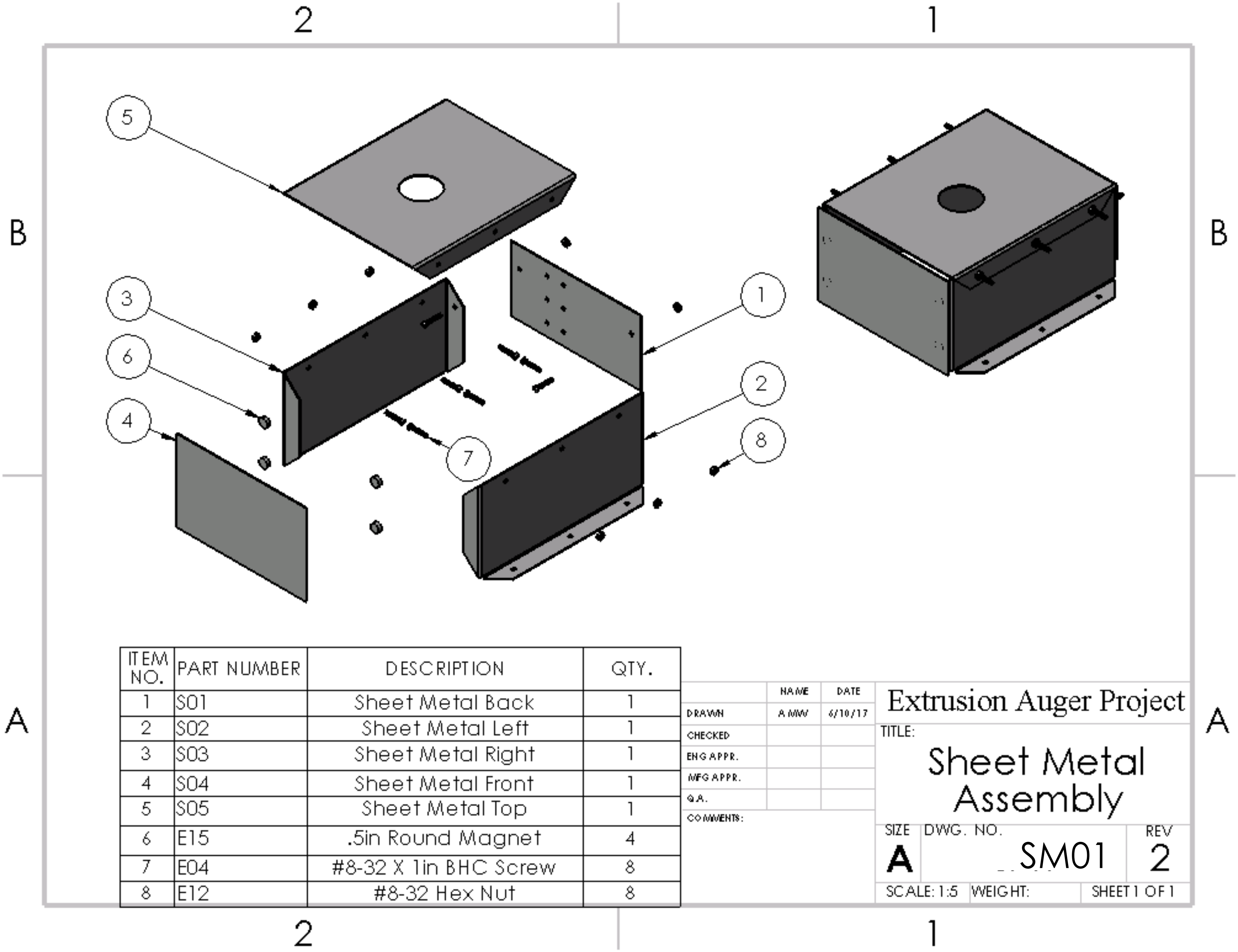


Figure I 22 – Part drawing S05.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	V01	Left Foot	1
2	V02	Right Foot	1
3	V03	Vertical Arm	2
4	V04	0.375in-16 X 3in Threaded Rod	1
5	E13	0.375in-16 Galvanized Hex Nut	2
6	E06	#8-32 X 2in BHC Screw	4
7	E12	#8-32 Hex Nut	4
8	HA01	Horizontal Arm Assembly	1

Figure I 23 – Assembly drawing SA01.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	S01	Sheet Metal Back	1
2	S02	Sheet Metal Left	1
3	S03	Sheet Metal Right	1
4	S04	Sheet Metal Front	1
5	S05	Sheet Metal Top	1
6	E15	.5in Round Magnet	4
7	E04	#8-32 X 1in BHC Screw	8
8	E12	#8-32 Hex Nut	8

Figure I 24 – Assembly Drawing SM01.

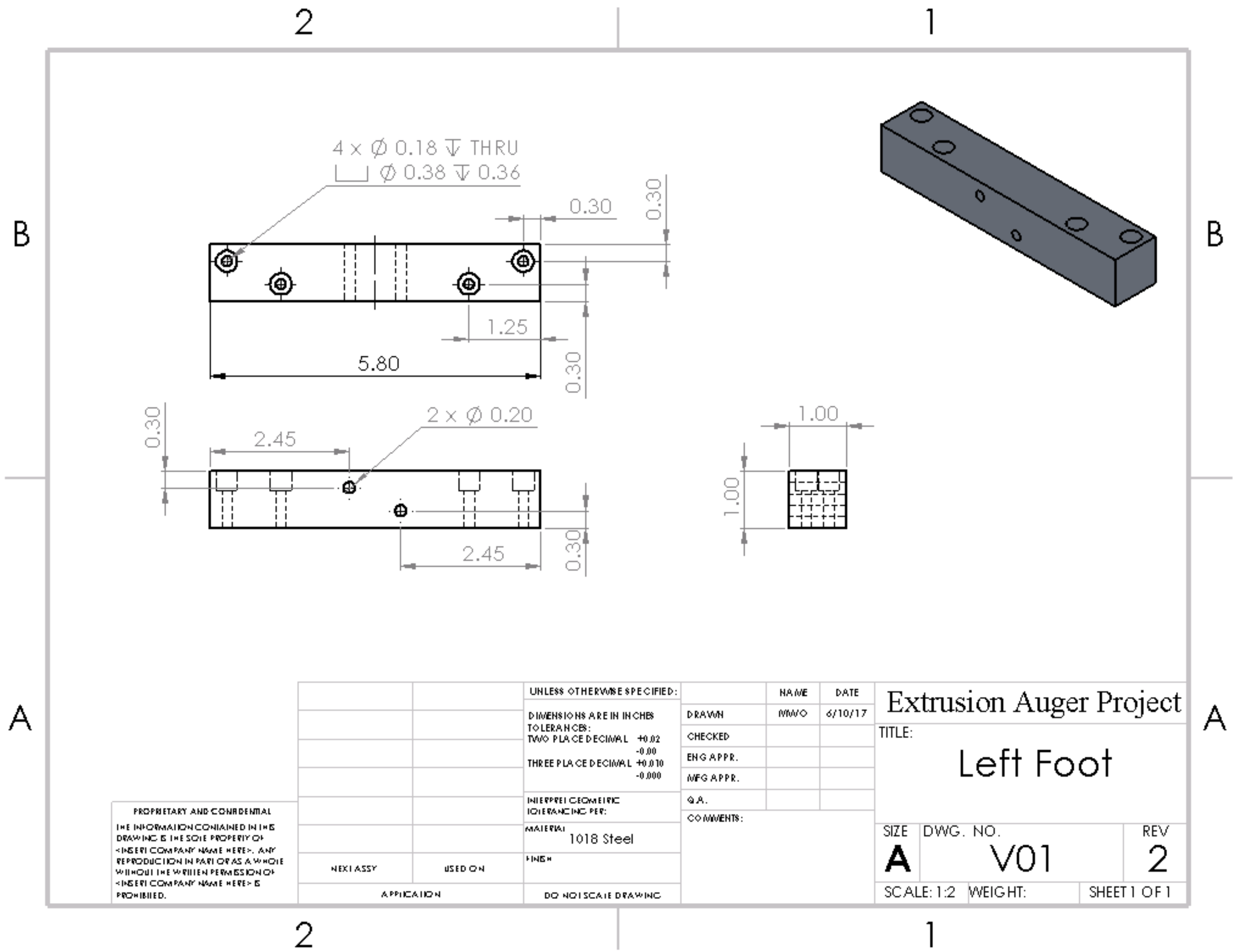


Figure I 25 – Part drawing V01.

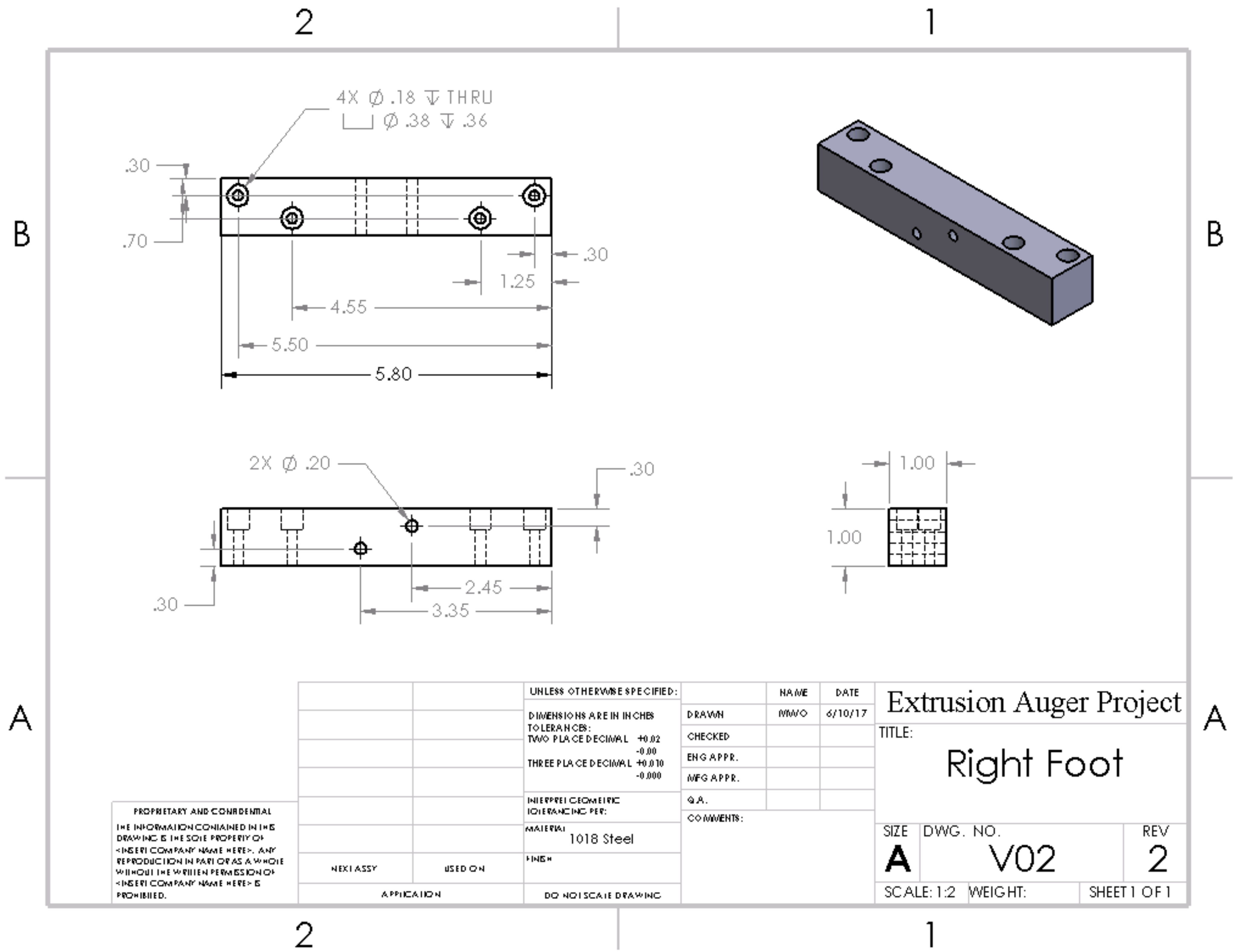


Figure I 26 – Part drawing V02.

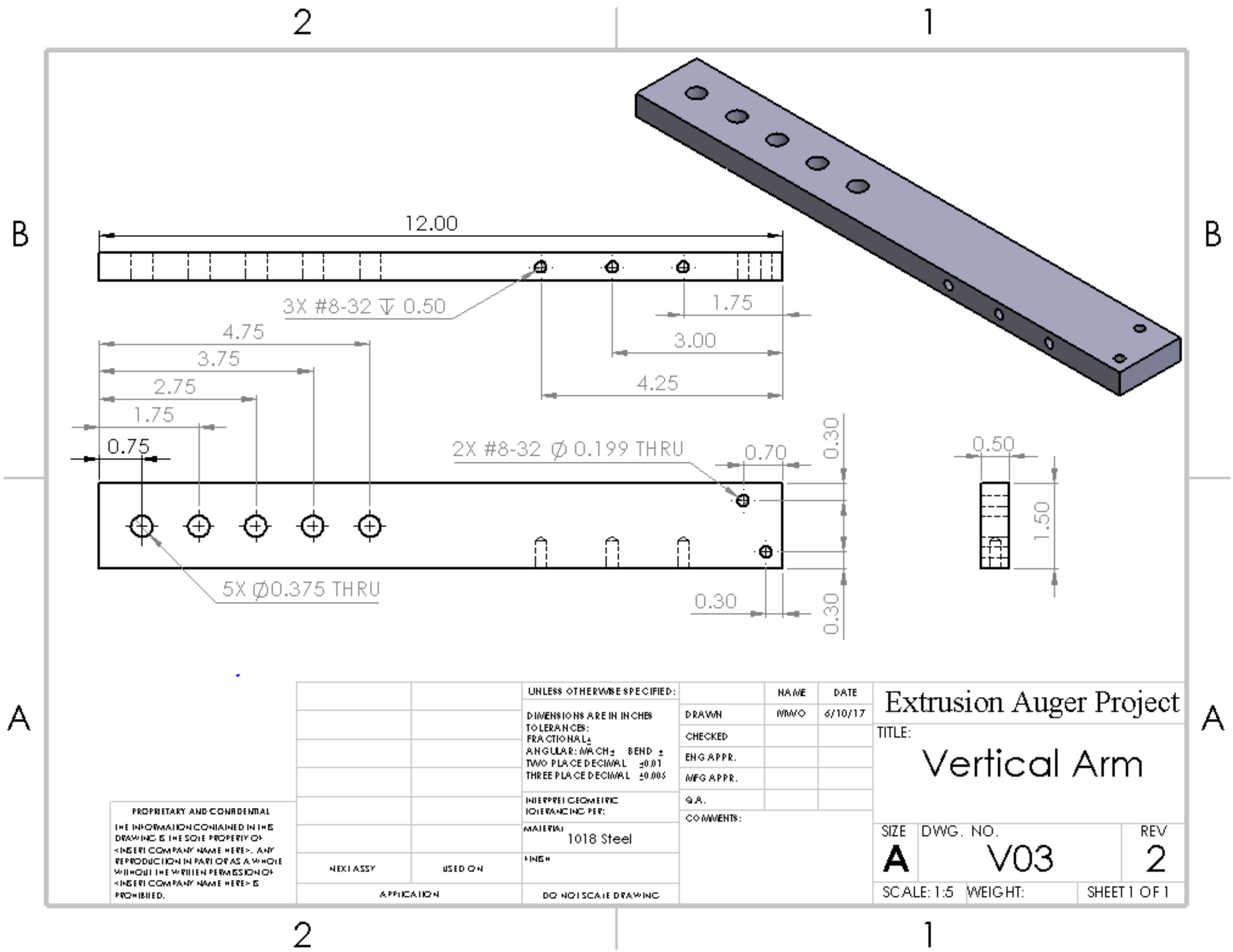


Figure I 27 – Part drawing V03.

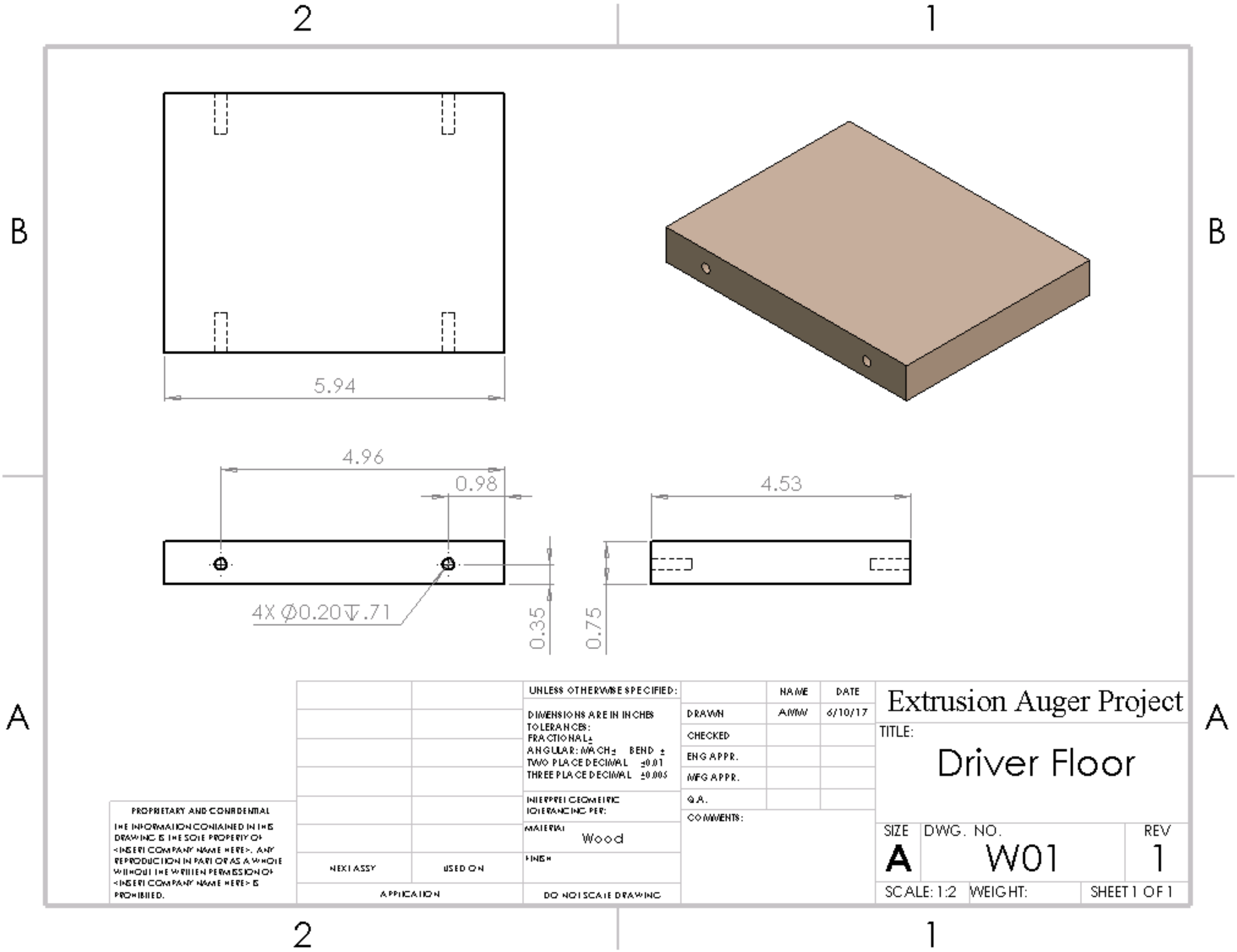


Figure I 28 – Part drawing W01.

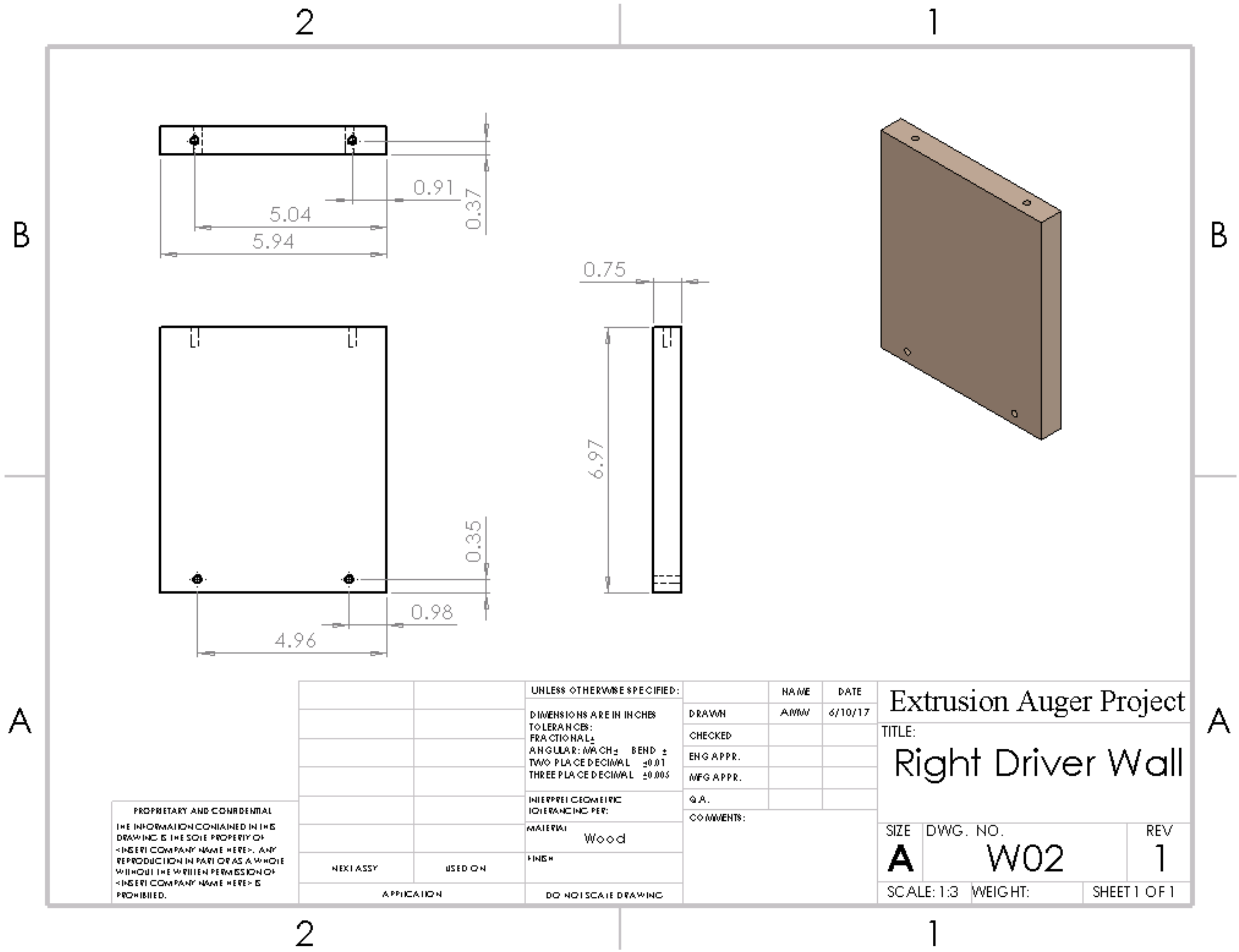


Figure I 29 – Part drawing W02.

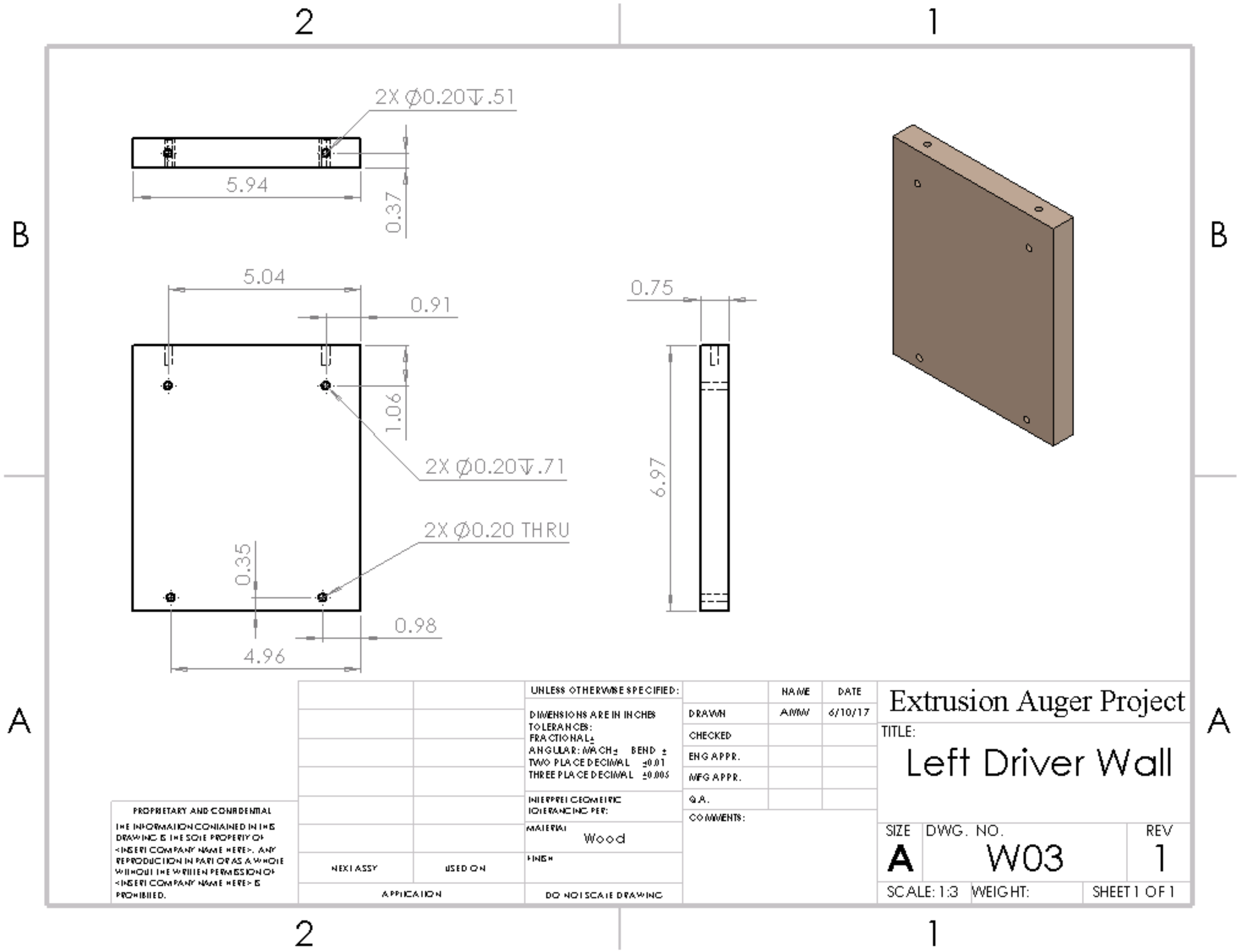


Figure I 30 – Part drawing W03.

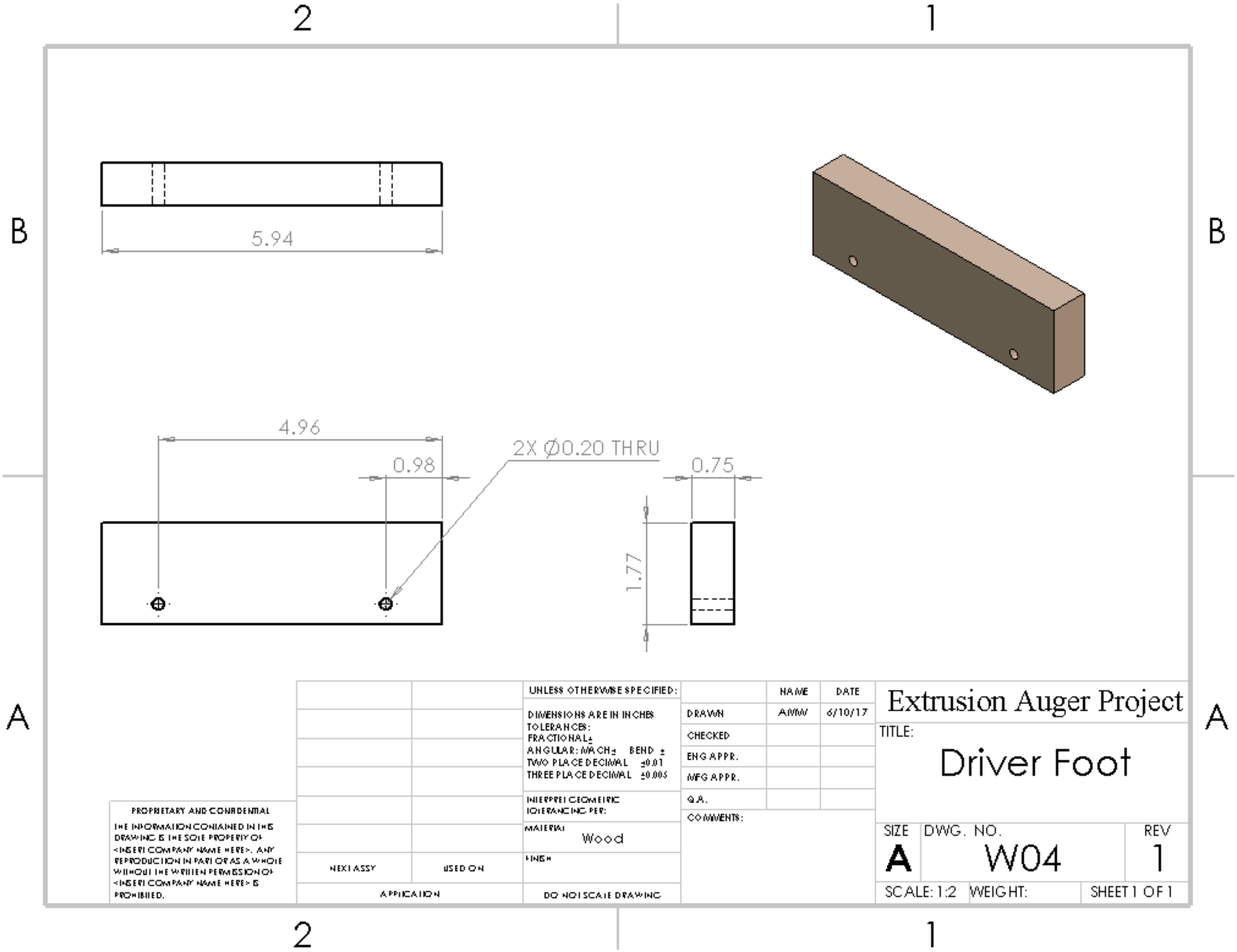


Figure I 31 – Part drawing W04.

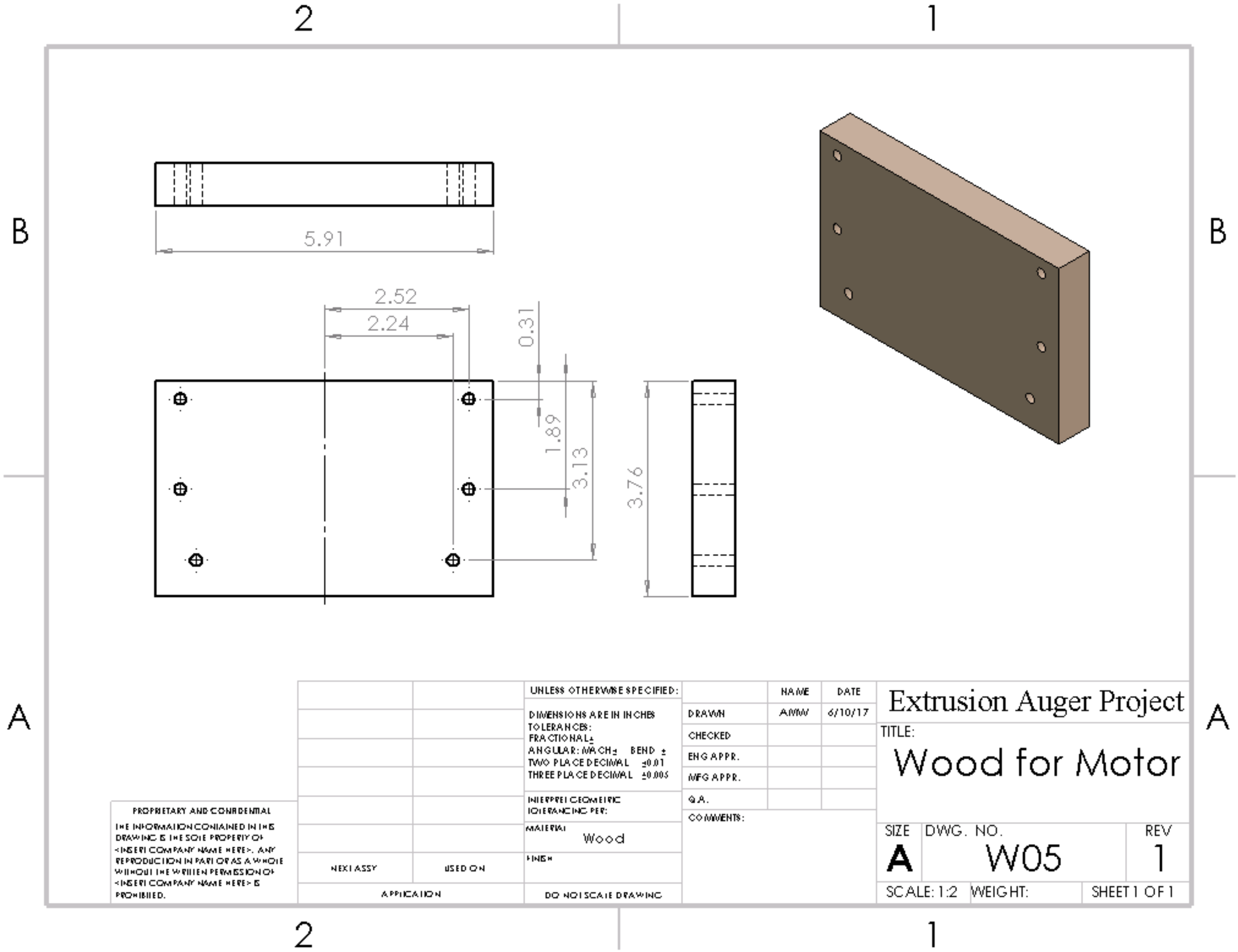


Figure I 32 – Part drawing W05.

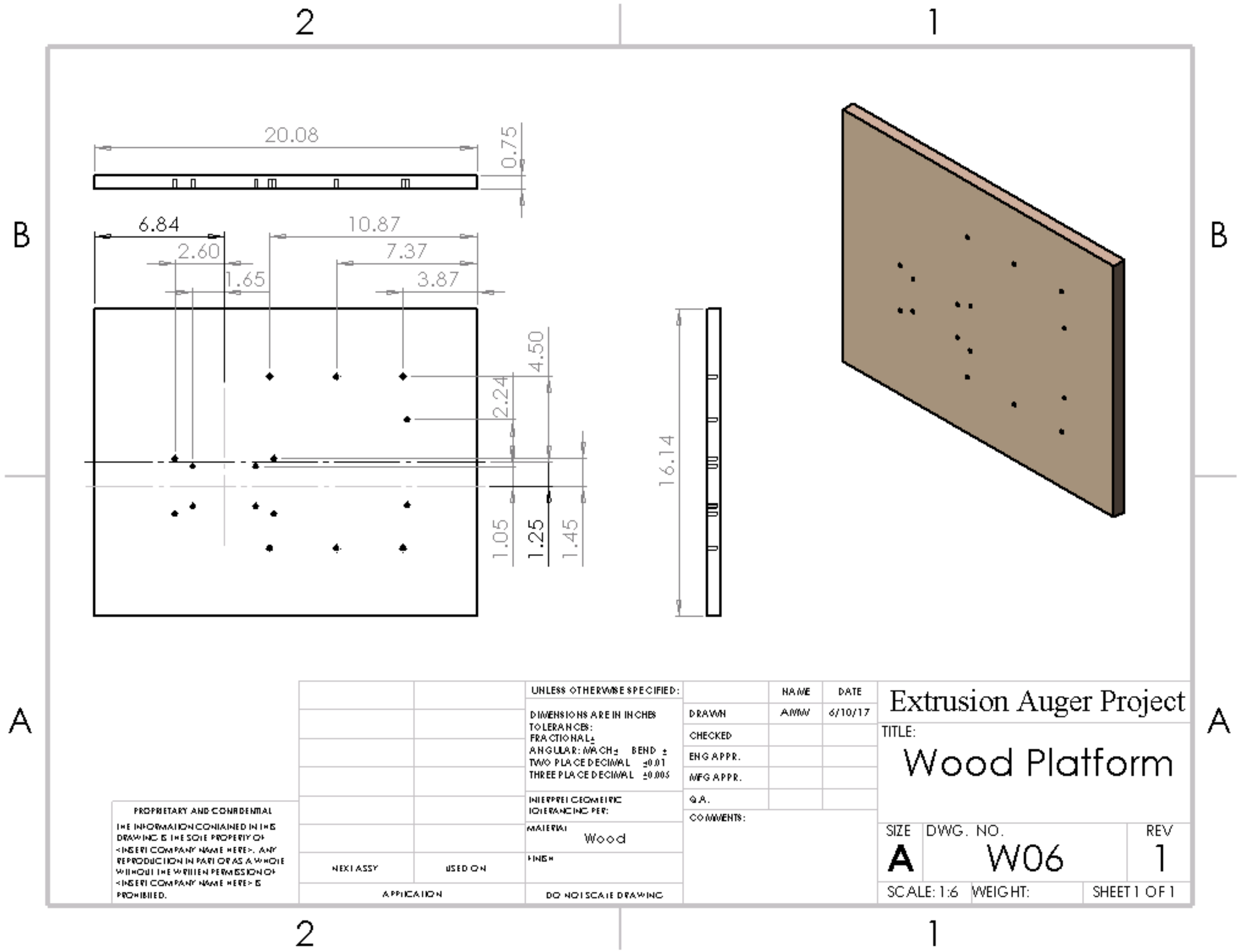


Figure I 33 – Part drawing W06.