SFSA Cast in Steel Competition

Viking Axe Final Report

Team Freyja
Steven France
Michael Seitz
Natalie Quintanilla
Erick Zamora
Benjamin Duong

Advised by:
Dr. Dika Handayani
Dr. Victor Okhuysen

Industrial and Manufacturing Engineering

Cal Poly Pomona

8 April, 2019

Table of Contents

ABSTRACT **3**

1. INTRODUCTION **3**
1.1. Project Management 3
1.2. Literature Review 5

2. DESIGN **10**
2.1. Design Selection 10
2.2. Alloy Selection 10
2.3. Production Processing Selection 11

3. MANUFACTURABILITY **13**
3.1. Design Analysis 13
3.2. Final Design 14
3.3. Pattern Production 16
3.4. Prototyping 30
3.5. Production Processing 33

4. QUALITY & PERFORMANCE **36**

5. CONCLUSION **38**

6. WORKS CITED **40**

ABSTRACT

Since early on, history axes have been used as weapons and have evolved in the way they have been manufactured throughout the years. For this project, the production of a viking axe by casting was the main goal. In order to achieve this objective, there were several stages that had to be explored before a final product was made. These stages included research, design, tooling fabrication, axe production, final assembly and testing. The alloy we decided to go with was Cast Stainless Steel CA6NM. With the help from our industry partner, Strategic Materials Corporation, and the use of casting technologies(solid modeling, rapid prototyping, and casting simulation), we were able to design and produce a viking axe that met all of our design goals.

1. INTRODUCTION

1.1. Project Management

Figure 1 shows the original Gantt Chart generated for the viking axe project. Starting in November, the group began semi-weekly meetings to combine input on the axe design, casting technology, alloy selection, and historical influences. Once design aspects were identified that the group wished to incorporate, work began to generate a 3D model to assist in design realization and rapid prototyping.

Once a final design was achieved and the group was satisfied with a plastic prototype, the next step was to generate the required model to use in casting simulation and matchplate construction. Using Solidcast, a gating system and riser system were developed and tested to insure adequate fill temperatures and metal fill volume during cooling. Once satisfied with the simulation, the matchplate was fabricated and a test part was poured in aluminum using the schools foundry equipment.

After pouring a successful test pour, the group worked with a local foundry to assist in casting the final design in the required alloy. These final axes were then heat treated, polished, and assembled with the axe handles.

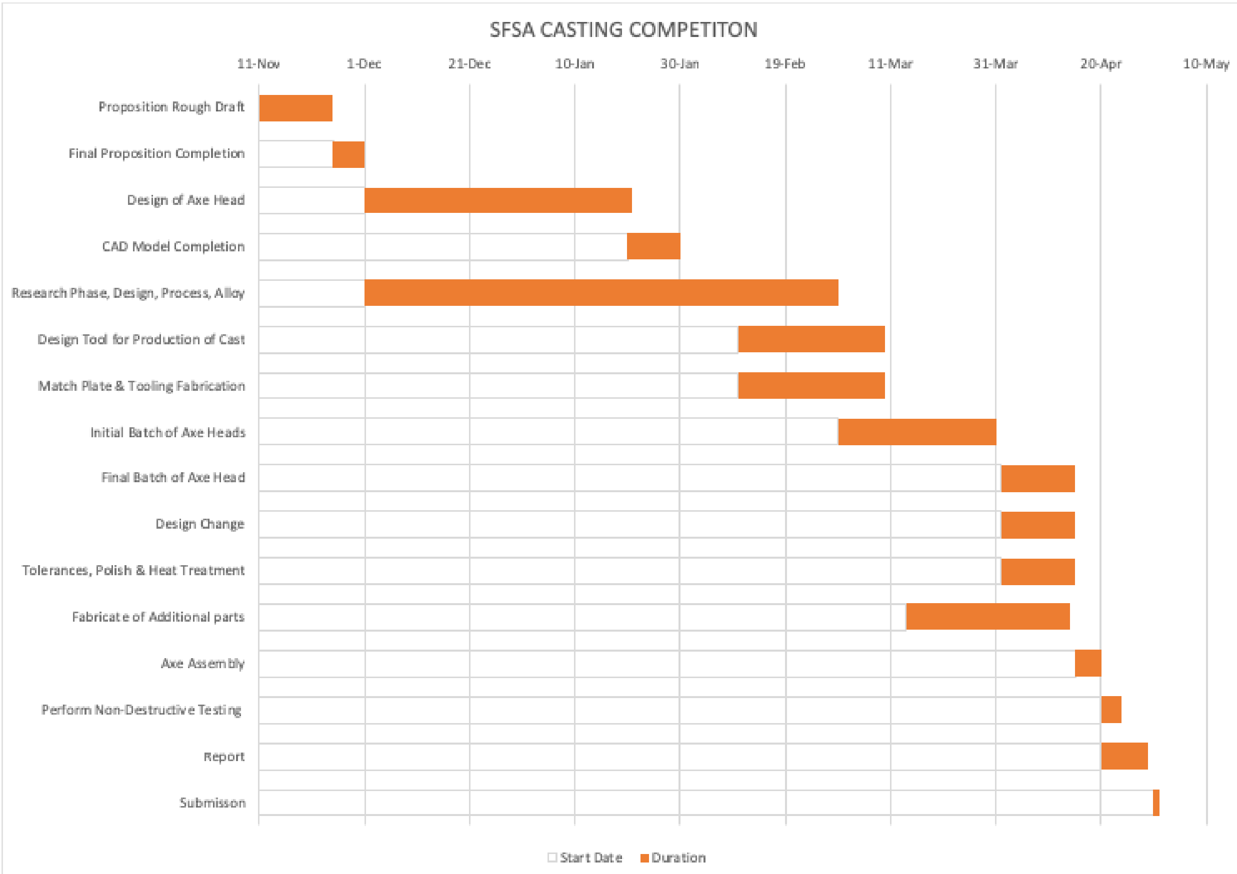

Figure 1: Original Gantt Chart

Figure 2 shows an adjusted Gantt Chart for the final project. Due to scheduling difficulties, the project was paused over winter break. Previously some tasks were planned to be run in parallel, but the final project ran mostly in series. Additional time sinks were also realized throughout the project as design and production tasks took more time that initially estimated. Additional time was often lost due to delays from outside requirements such as additional school projects.

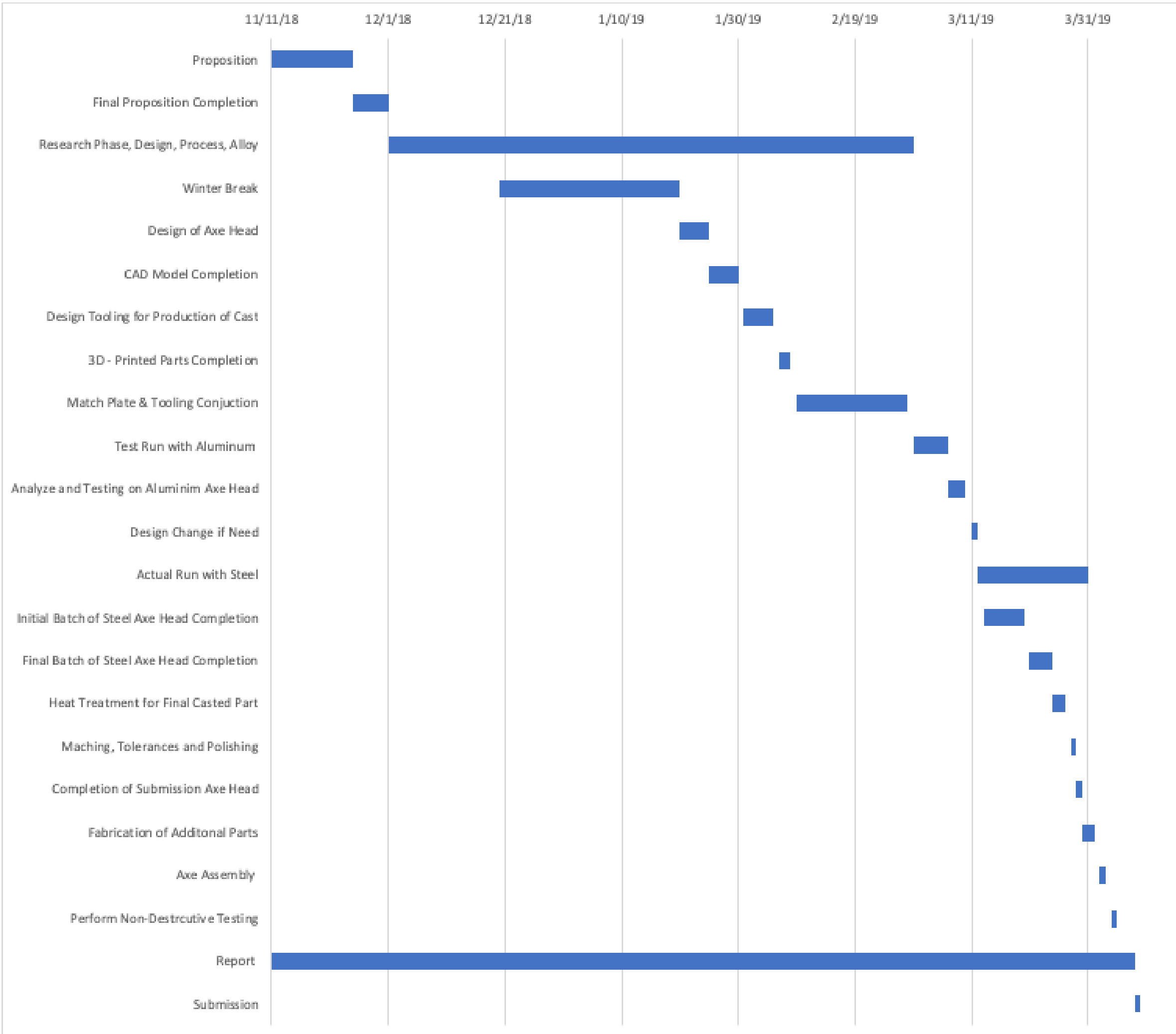

Figure 2: Updated Gantt Chart

In the final outcome of our gant chant changes were made that differed from the original gantt chart. Based on the casting method that was selected additional work was to be added. Ergo, changing the gant chant completely to accommodate for any unforeseen events due to casting process and the changing of casting rule guidelines. As well as more testing was conducted to better off our chances in the competition. Additionally adding more manufacturing time in design to make our axe as unique based off our team.

1.2. Literature Review

In our quest to produce an accurate historical viking axe, we researched viking era axes. In our findings, we discovered that axes in the viking age were a primary tool not just for warriors but for common folk as it was a readily useful tool to cut wood and could be use for defense if needed. However, battle viking axes were on a completely different standard of craftsmanship.

At first, many of us rush to a single conclusion when they hear the word “viking axe,” the image most likely is of a massive two handed battle axe with intricate designs on the axe head and beautiful handle with nordic imagery and design, held by a burly bearded man with a horned helmet. In reality, we found that viking axes were actually very simple in design, with a simple axe head and simple straight non-ergonomic handle, which main intended purpose was to be lightweight in use of combat. Almost all axes were found to be made out of iron except those which were truly intricate made for decorated warriors composed of some precious metals, such as copper and silver.
We also found some axe did have intricate designs in the axe head but like mentioned previously it was mostly in cases of warriors who had a high ranking in viking era. Throughout most of our investigation we looked at axes made in the 10th through the beginning of the 12th century.

In viking era, our discoveries of viking axes is that they were all made of iron and came in a variety of shapes and sizes depending on the century. In the 10th century, we found out that axes were primarily made of iron and were single edged as seen in **Figure 3.** We can see a clear representation of what a 10th century axe head looked like.

Figure 3: 10th century axe head

In our discoveries, we realized that axe heads came in a variety of geometries. We found that most dimensions of the cutting edge of early viking axe in the 11th century were approximately around three to six inches in length. Later the Vikings applied their craftsmanship to much larger axes such as the *Breið-øx*, as seen in **Figure 4** below, which had a crescent shaped and measured anywhere from nine to eighteen inches in length. Some of the edge of the axe was made of hardened steel welded to the iron head. The steel permitted the axe to hold a better edge than iron would have allowed. This 11th century axe,the *Breið-øx*, was a large inspiration to what would become the final axe design.

Figure 4: 11th century axe heads

Many historic viking axes had very thin cross-sections at the edge of the axe as seen in the left picture from **Figure 5**. These thin axe heads were lighter for combat but were very delicate. We made our axe with a diamond shaped cross-section at the edge such as the modern axe seen on the left of **Figure 5**. This diamond shaped cross-section provided greater strength for the edge so it will not break on hard objects.

Figure 5: Wedge-shaped cross section

As seen in **Figure 6**, historic viking axes often came in two sizes, axes with small heads with a small haft which was used with one hand, or a large head with a large haft that was used with two hands. The one handed axe shafts were often about 28 inches while the larger ones were around 55 inches. Commonly, smaller axes were hidden behind shields or cloaks and then used in a sneak attack. The longer axes provided more range than a small axe and more power in an attack because it had more weight to the head.

Figure 6: Axe head to haft ratio

Curved axes were often used for a variety of moves in combat. These curves could be used to disarm the enemy by grabbing their weapon or shield and pulling it away from them. The axe could also be used for grabbing the enemy and pulling him in a direction he does not want to go, as seen in **Figure 7** above. These curved axes also had a point to them that could be used for stabbing or slashing that could cause serious injury to the enemy.

Figure 7: Hooked axe head

2. DESIGN

2.1. Design Selection

We wanted our axe to be as historical as possible but with our own individuality and modern touches. We made the axe of typical dimension of the viking era as found through our research into viking axes above, with a personal touch of runes that translate to CPP on the axe head for our own personal touch.

With our cutting edge around 9 inches in length, and the axe head height excluding the cutting edge of around 3.5 inches and a total width with the cutting edge of around 9 inches. When designing the cutting edge a arrow tipped blade shape was chosen, settling with a 30 degree angle used for contemporary modern blades. The viking axe eye was design to be similar in built as seen in **Figure 3** to form a squarish eye style like towards the back with a pointed eye as moving towards the cutting edge similarly used in viking era. As for the size of the viking axe including the handle it measures to be approximately 36 inches in length similar to an axe of that era. However, we implemented ergonomics to our design of our handle as most axe handles were circular and straight in characteristic and found it to be dull and uncomfortable. As well as the implementation of a grip using a woven pattern for when handling the axe.

The shape of the axe was primarily chosen from historical photos that we had reviewed. The axe head design was chosen because it followed a crescent moon structure seen in most cutting edges of the viking era. This design looked best as most other designs from viking era had straight angles and geometry.

To keep the sharpness and edge durability of the axe we decided to cast with an alloy that could withstand blows to hard objects without deforming or breaking. We made the cross-section of the axe diamond shaped for increased strength.

2.2. Alloy Selection

A hand full of considerations were taken into account when selecting the alloy this axe would be made out of. Priorities include high impact resistance, corrosion resistance, and acceptable hardness. With these characteristics in mind, a decision was made to use CA40 for its corrosion resistance and acceptable hardness. Due to time limitations, a compromise was made, and the alloy used was replaced by CA6 NM.

Though CA6NM does not have the same hardness achievable with CA40, it's high impact resistance and hardness would seem sufficient for the level of use this axe is expected to see.

2.3. Production Processing Selection

When analyze casting process selection, there was multiple ways to achieve what we wanted. We managed to narrow the decision based. On something familiar to our course curriculum. The two methods that we chose for this project was investment casting and sand casting. This was due to the familiarity, usability, and low cost. Ultimately deciding with sand casting as the use for this project.

The major things needed for sand casting are a pattern, a matchplate and flasks. The major characteristics of a cast produced by sand casting come from the sand itself. Green sand is used and is composed of sand, clay, and a bit of water to bind the mixture together. Molding sands are based of off eight characteristics which are refractoriness, chemical inertness, permeability, surface finish, cohesiveness, flowability, collapsibility, and cost.

Sand casting is relatively easy and consists of making a sand mold of the part that is to be casted. When using this method we knew we would two halves of a mold to create the axe pattern with. Careful design considerations were made in order to accommodate this limitation. This isn't ideal but due to our experience with this method we sought to work with the limitation of the procedure. We decided to place our parting line directly in the center of the axe running along the edge of the blade. This parting line is along a flat plane and is at the mid way for our axe which is desirable because we are using dense metal. This was the first consideration taken into account as the first step in sand casting was to make our matchplate.

By using SolidCast software, we were able to determine the need for risers and if we had an appropriate gating system. These features also had to be placed into our sand mold, on the cope portion, to allow for a solid casting of the desired dimensions. Another feature that we had to add to our design was a core to create the hole in the axe head for the handle.

We analyzed the pros and cons of different casting methods to better further the advancement of our axe project. We focused on available resources that would allow us to perform the best cast possible for the competition looking at specific key factors. Being that investment casting and green sand casting where options placed on the table with companies allowing us to use their facilities to undertake the challenge of making the axe head. We analyzed the pros and cons of sand casting and investment casting to choose the best alternative possible.

First, we looked at surface finish as we wanted to make sure that our surface finish could be up to par with the other competitors. We knew that with investment casting we could produce a much higher quality of surface finish when casted, this was due to the fact that the metal replicates the texture of the sand when poured with green sand but since investment casting uses a wax no surface transfers over to the casted part. We looked for a solution to combat this, we analyzed different grain size of sand that would be able to give us really good surface finish if chosen to proceed with green sand casting. When trying to identify a sand we also took into account permeability as it would reduce the porosity but could also affect the surface finish.

The second criteria for us was size and dimensional tolerances in the amount of production of axe heads. We knew that sand casting was mainly used in production of larger parts, while investment casting is used to make more intricate designs patterns and use to make several pieces. Being that our axe was quite large we were unsure of being able to produce this through an investment casting scenario as maybe tooling and gating system would have to be must larger, and did not not require as many axe heads to be built. Although knowing that we were in a disadvantage for dimensional tolerances, as investment casting produces higher dimensional tolerances we didn't see this as an issue as our model did not have intricate etchings on the axe head. As well as we knew that if heat treated most likely we would have to machine.

Lastly, our third criteria was in terms of costs and time, sand casting is a lot cheaper than investment casting. It also has a shorter lead time as the main tooling required is the pattern itself. Investment casting requires the use of wax patterns on a tree that are injected to produce the mold. Having this in mind, investment casting has a higher production rate than sand casting but, for the purpose of this competition this was not required as we only needed to produce one axe along with several prototypes.

3. MANUFACTURABILITY

3.1. Design Analysis

In order to collaborate on the axe design effectively, the group used 3D printing to help bring light to design changes and achieve a better perspective on size and scale of details.

The initial revision of the axe was focused strictly on incorporating required design elements. Once the model was finished, a sample of the axe was printed to discuss further additions and changed. The second version of the model focused more on bringing the axe features into an acceptable scale such as blade length and overall scale. Figure 8 shows a comparison between the first axe design and the final axe design.

Figure 8: First (left) and Last (right) axe designs

One feature that was revised more than others was the eye profile to mate the handle and axe head. The handle used was an off-the-shelf replacement handle. The initial design disregarded any particular eye shape in favor of reviewing the general axe size and geometry. Once a sample handle was acquired, measurements were taken of the mating surface, and samples of the eye were printed to perform test fits and finalize a proper mating profile.

3.2. Final Design

The final axe design included all of the features that were initially required. Some of the notable features include an arrowhead shaped blade profile, a square butt, a hooked axe beard, and pointed lugs near the axe shoulder. The curves of the axe were carefully designed to create a smooth flow between all of its surfaces and profiles, with as few hard lines as possible. The eye was designed to accept a commercially available axe handle that adds to the ease of manufacturing, reducing the time and resources needed to finish a unit. **Figure 9** is an engineering drawing of the final design with an isometric view.

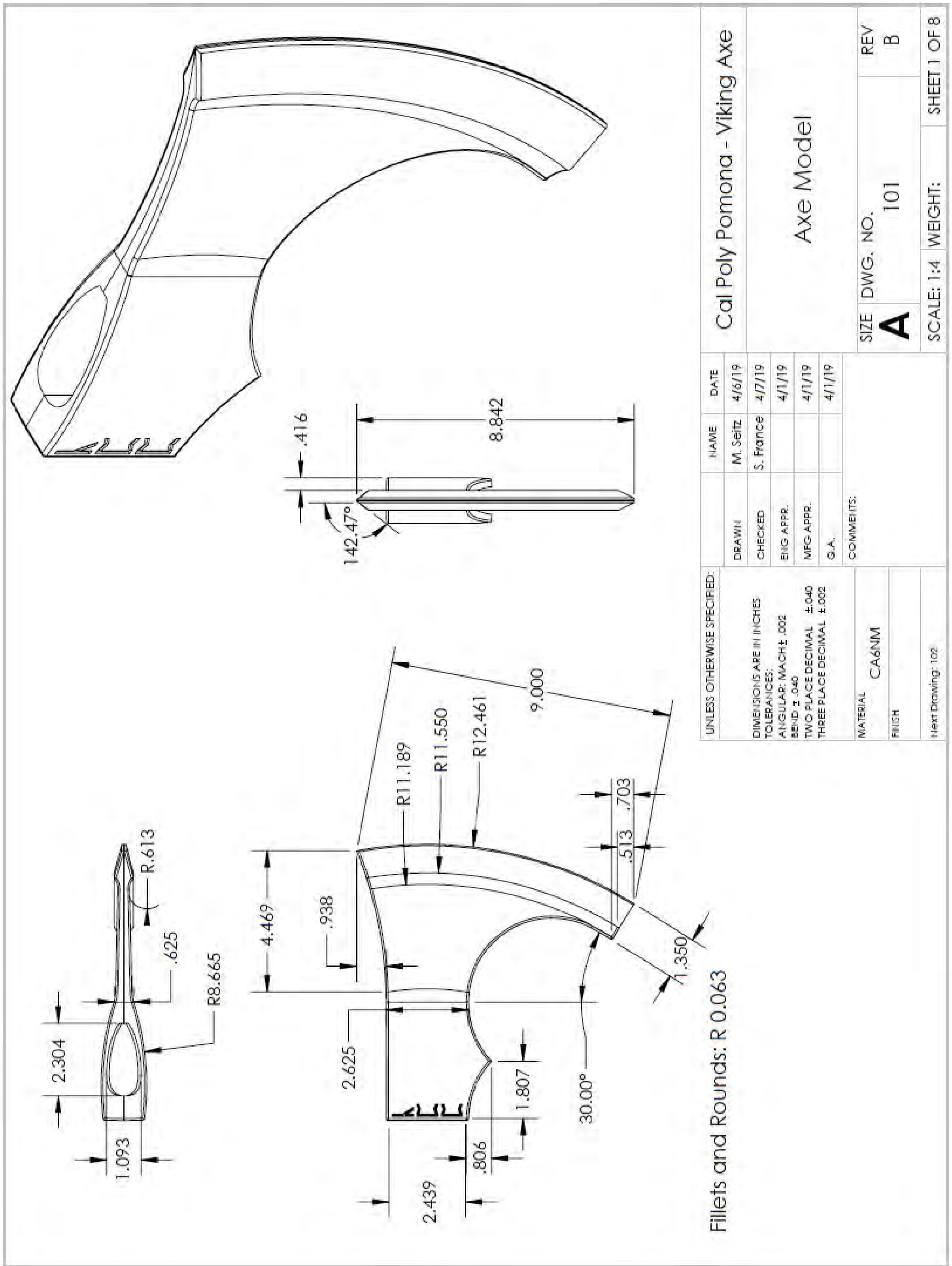

Figure 9: Axe Model

3.3. Pattern Design and Production

With the final design in hand, the model was revised to include features necessary to creating a good sand casting. The whole casting was volumetrically scaled 4% to help account for the expected shrinkage of the steel casting (Schleg, 2006). Any sharp corners were given a minimum radii of 1/16". Draft analysis was run on the model and any vertical surfaces were given a minimum of 2° draft. Pin holes were also modeled into the bottom of the pattern components so that dowels could be installed and insure alignment between the two sides of the matchplate as well as different components on the same side of the plate.

In order to better estimate the proper riser size, many different iterations of the casting design were simulated using solidcast to test for acceptable feed temperatures and density after solidification. **Figure 10** shows the final simulation results. The yellow bodies show any density estimated to be lower that 99%. **Figure 11** through **Figure 20** are engineering drawings generated for the matchplate assembly and corebox.

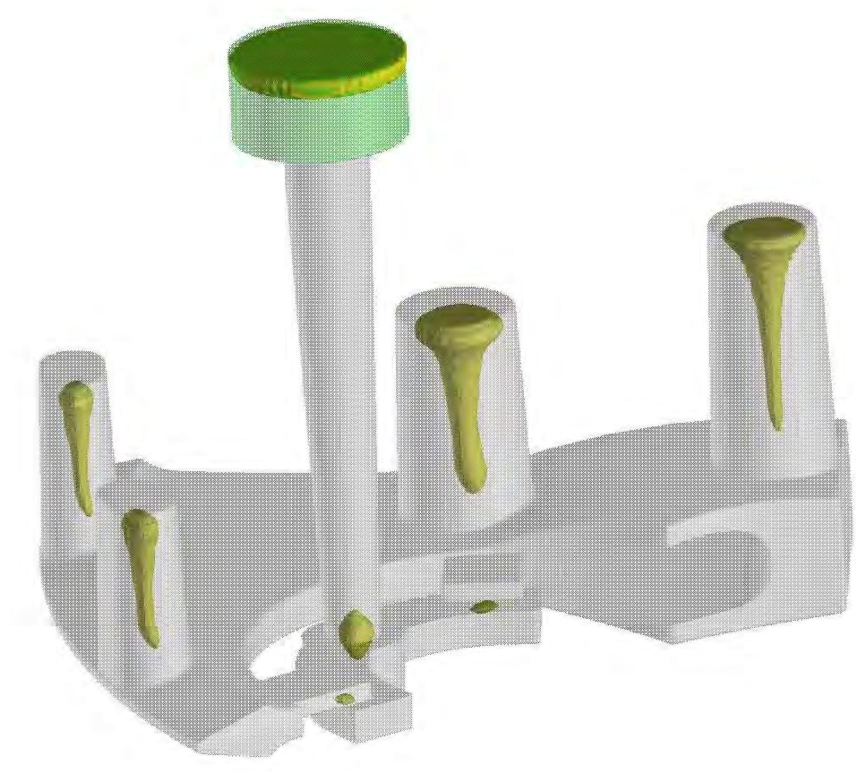

Figure 10: Solidcast screen shot

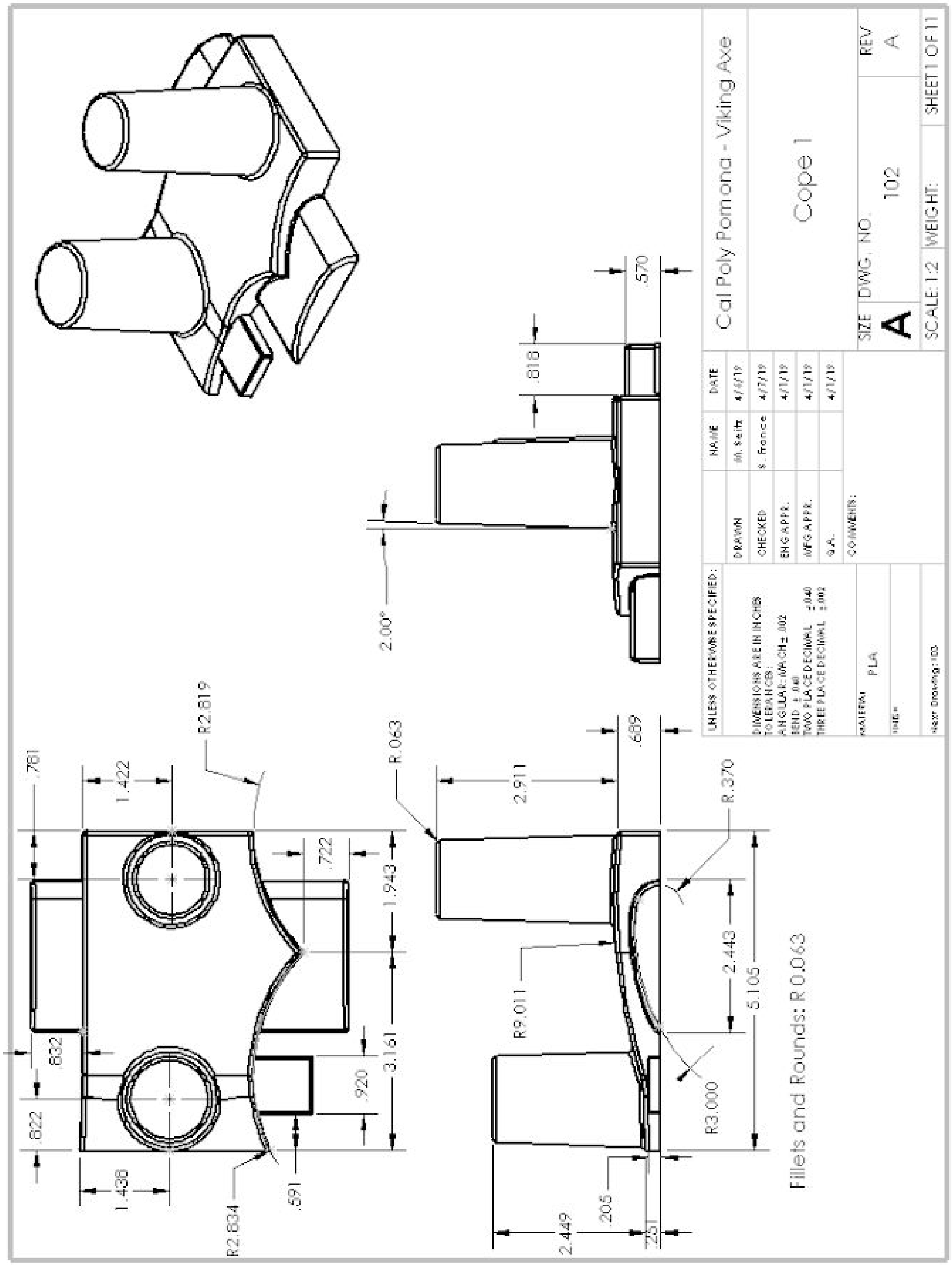

Figure 11: Cope Component 1

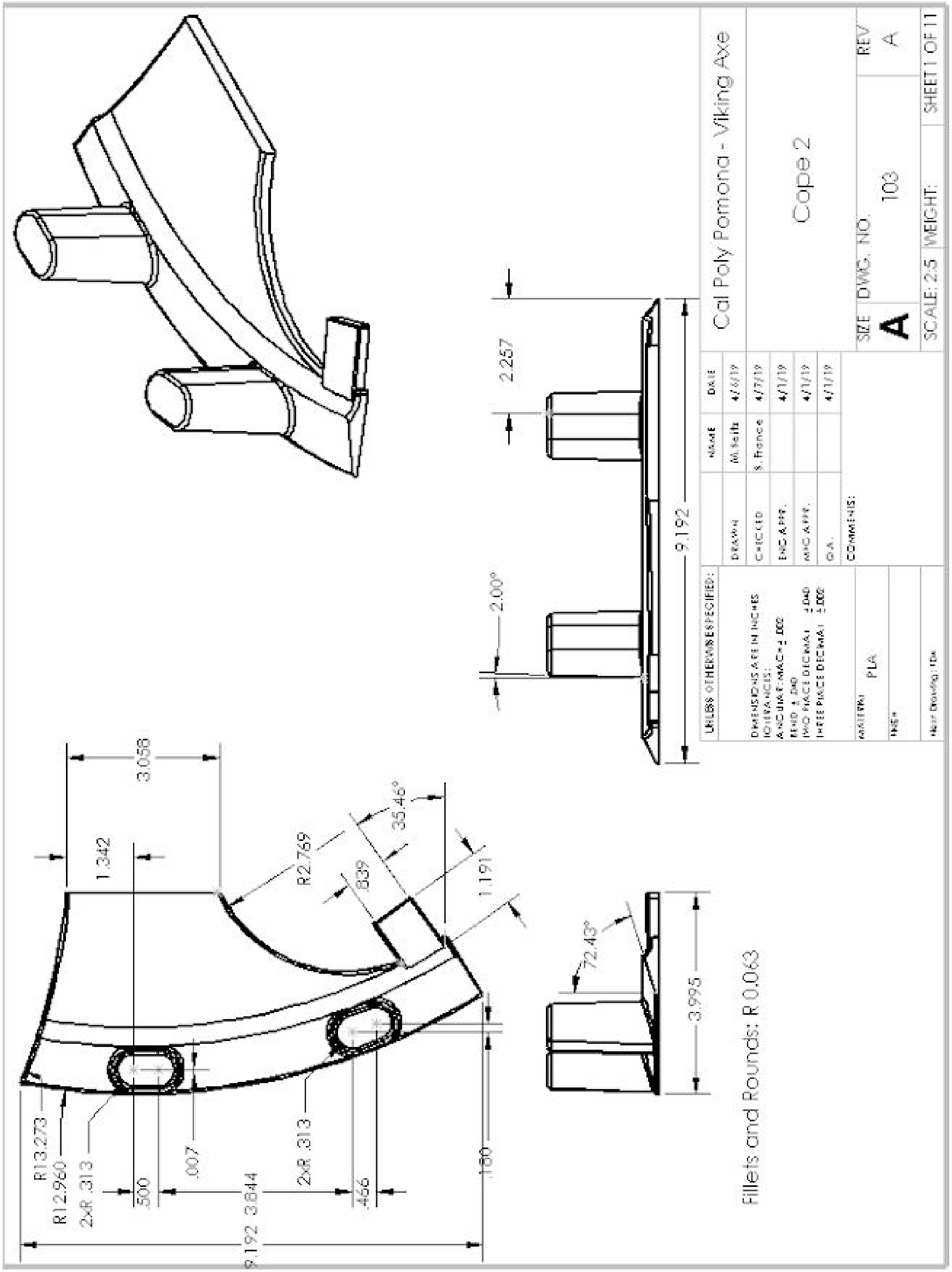

Figure 12: Cope Component 2

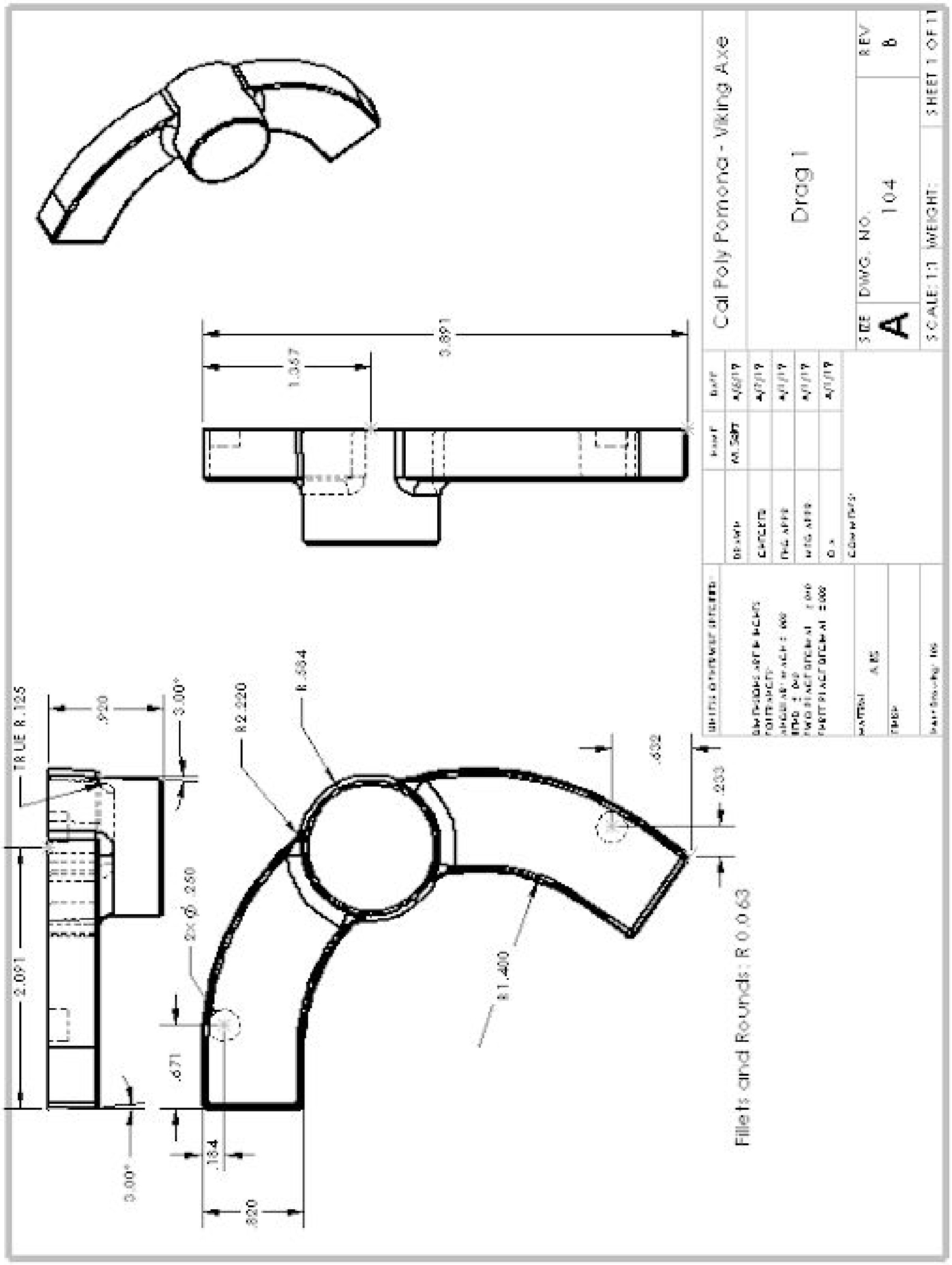

Figure 13: Drag Component 1

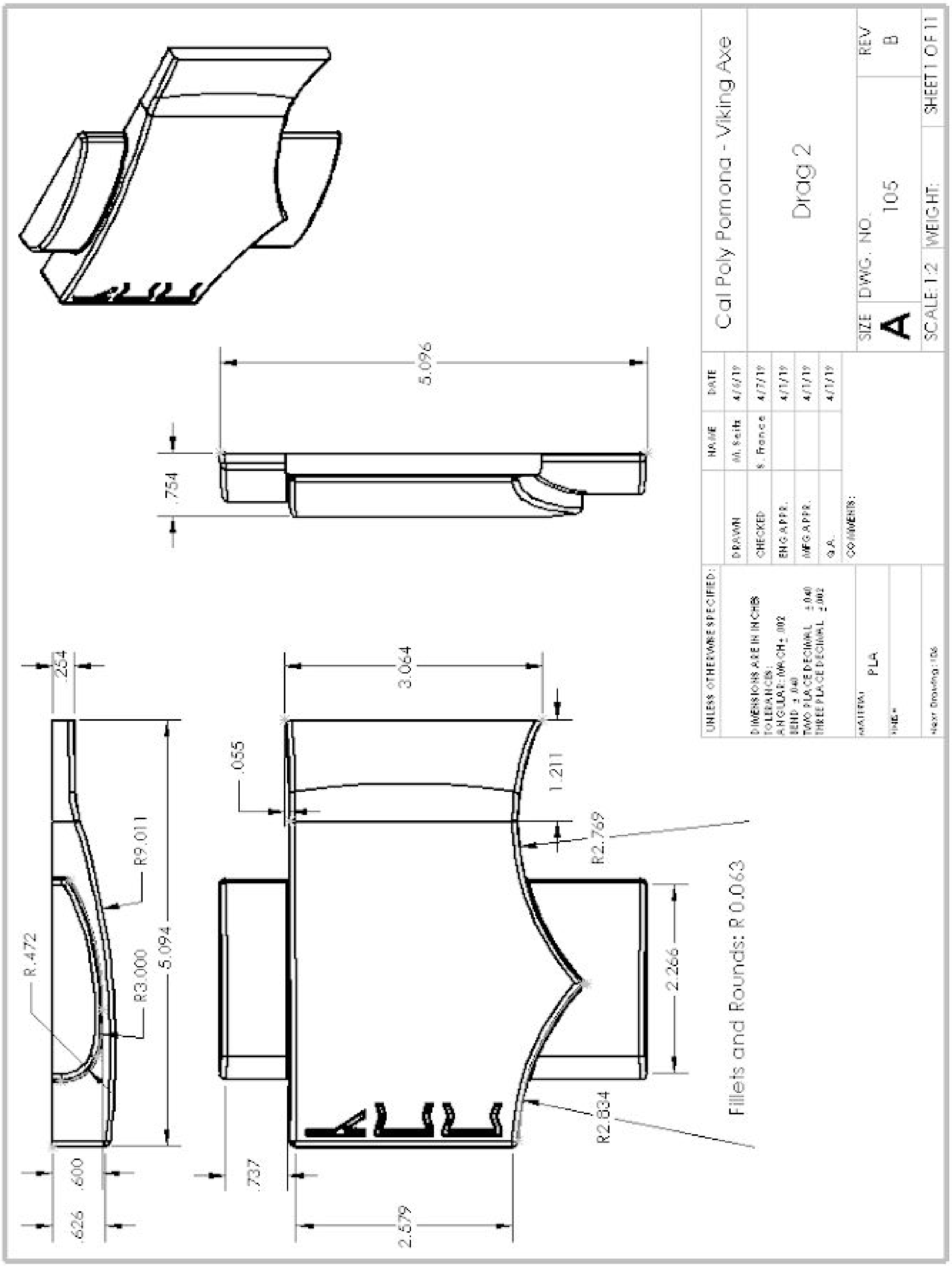

Figure 14: Drag Component 2

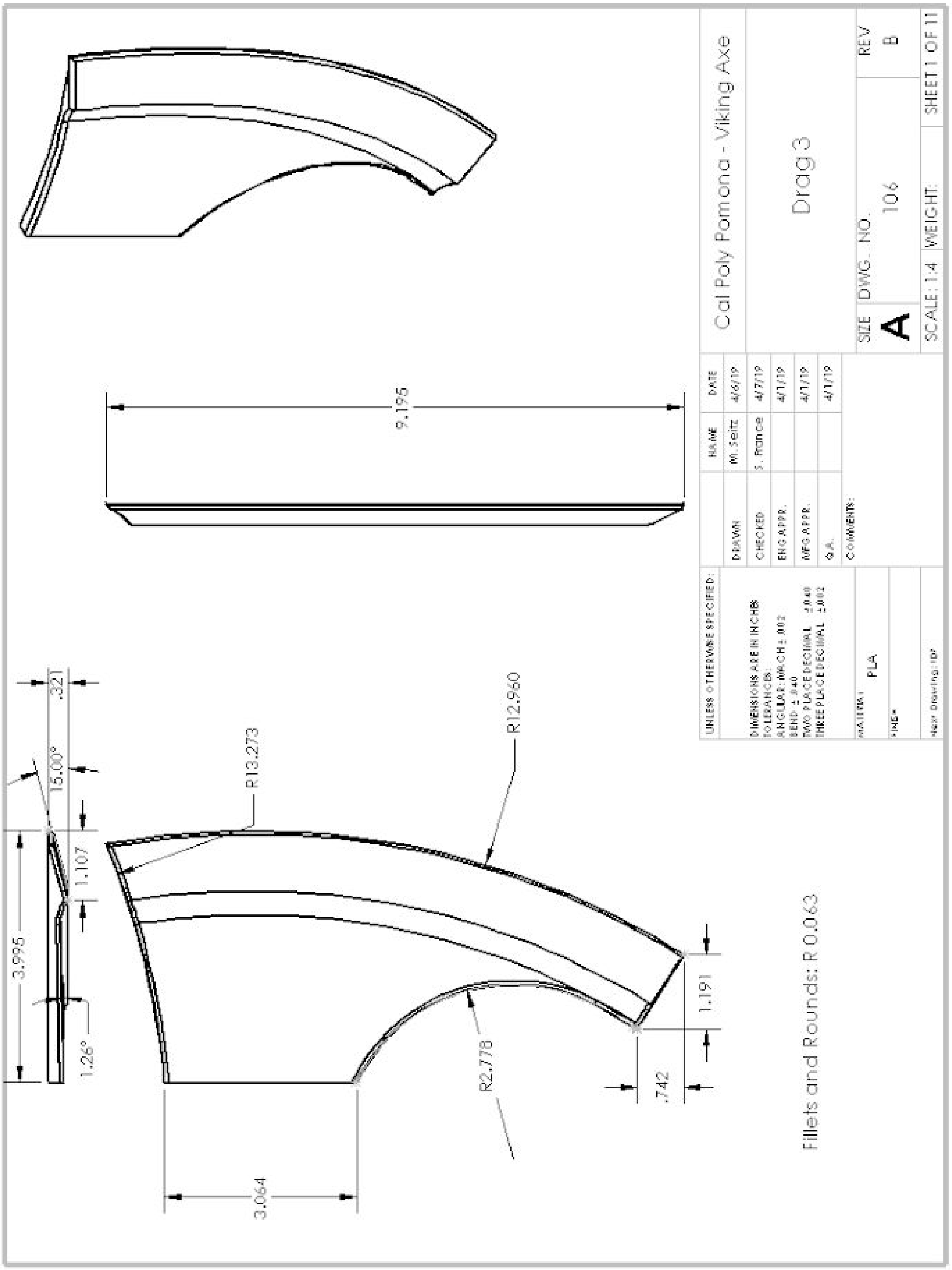

Figure 15: Drag Component 3

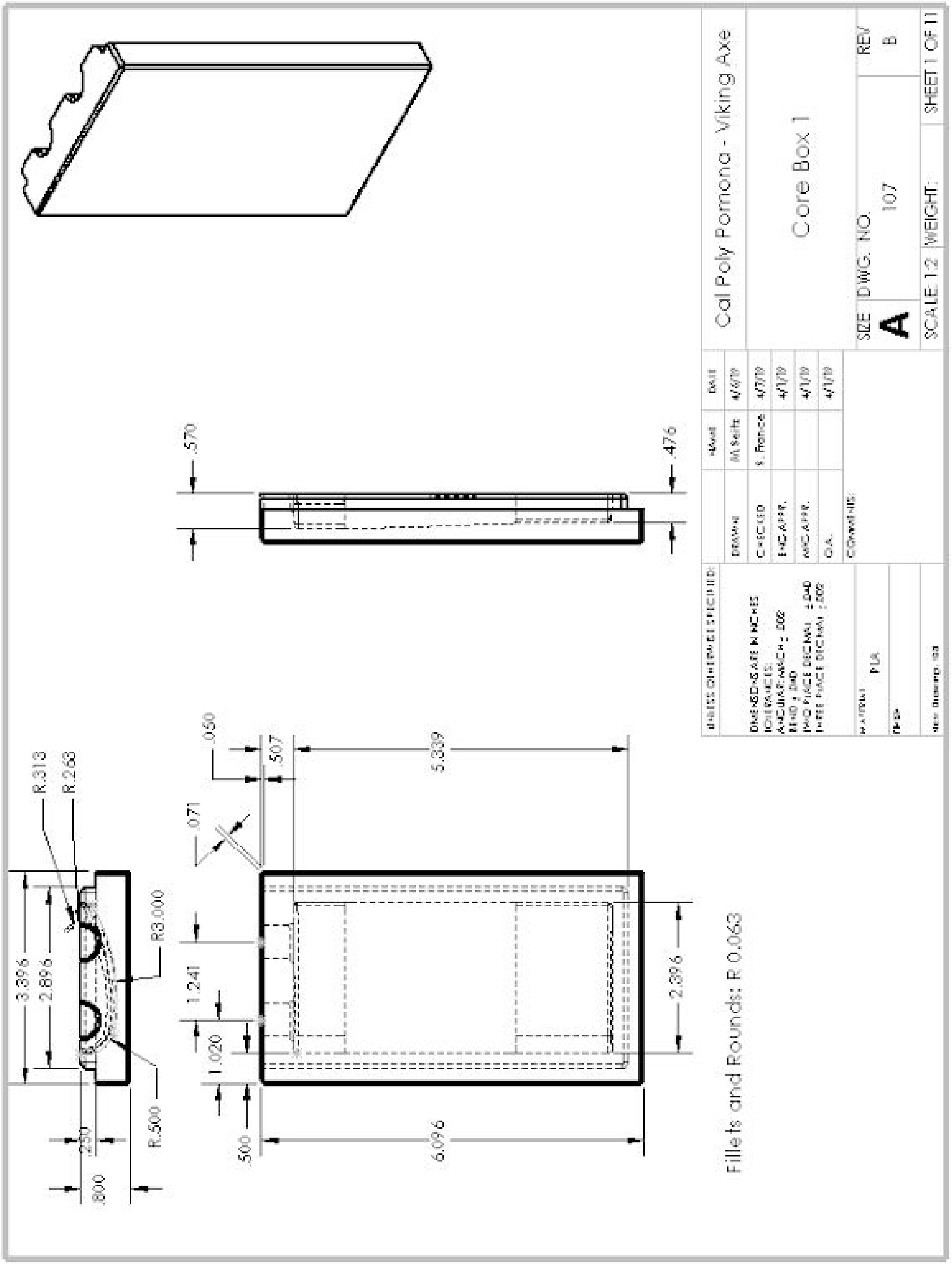

Figure 16: Core Box Component 1

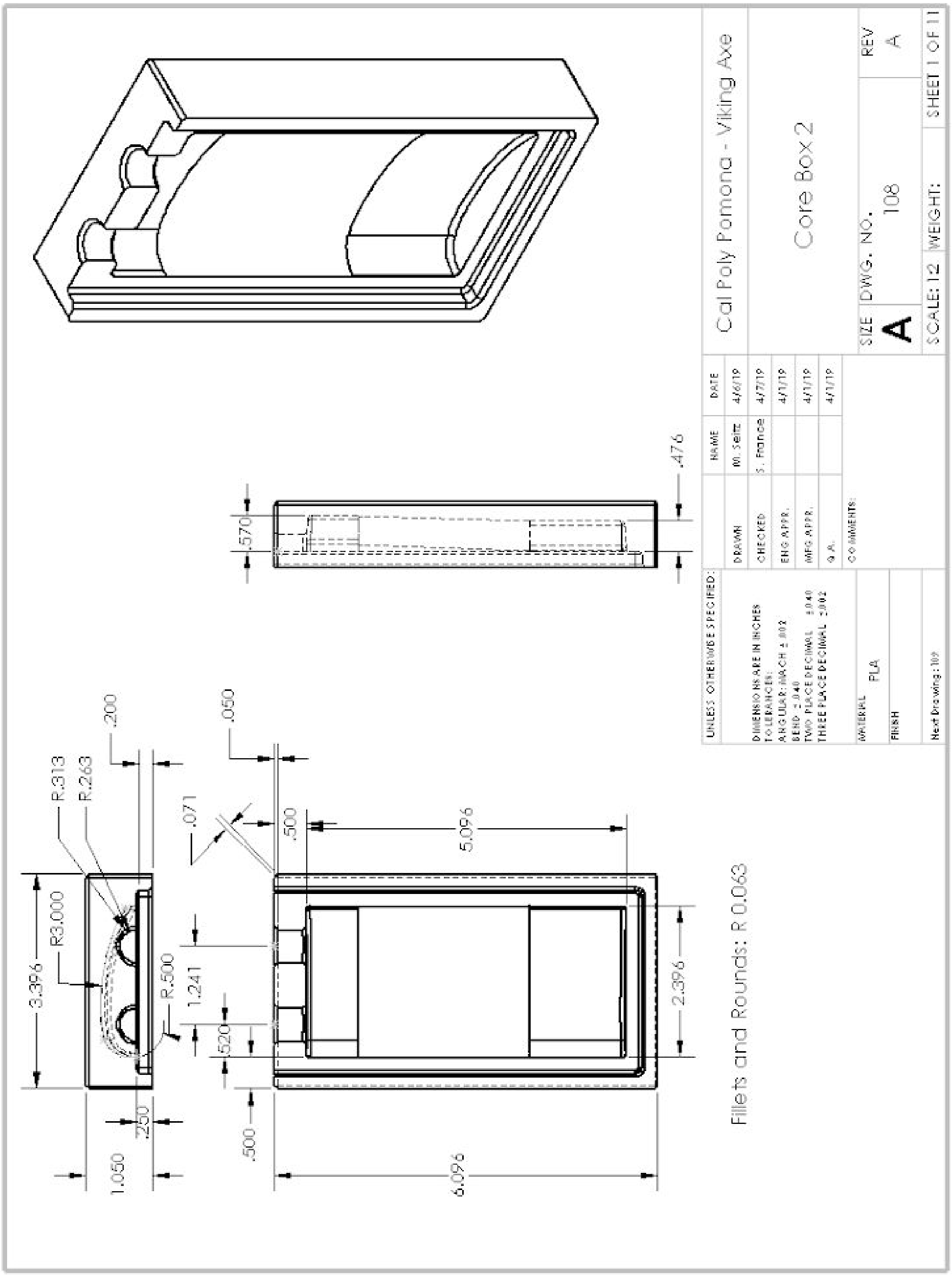

Figure 17: Core Box Component 2

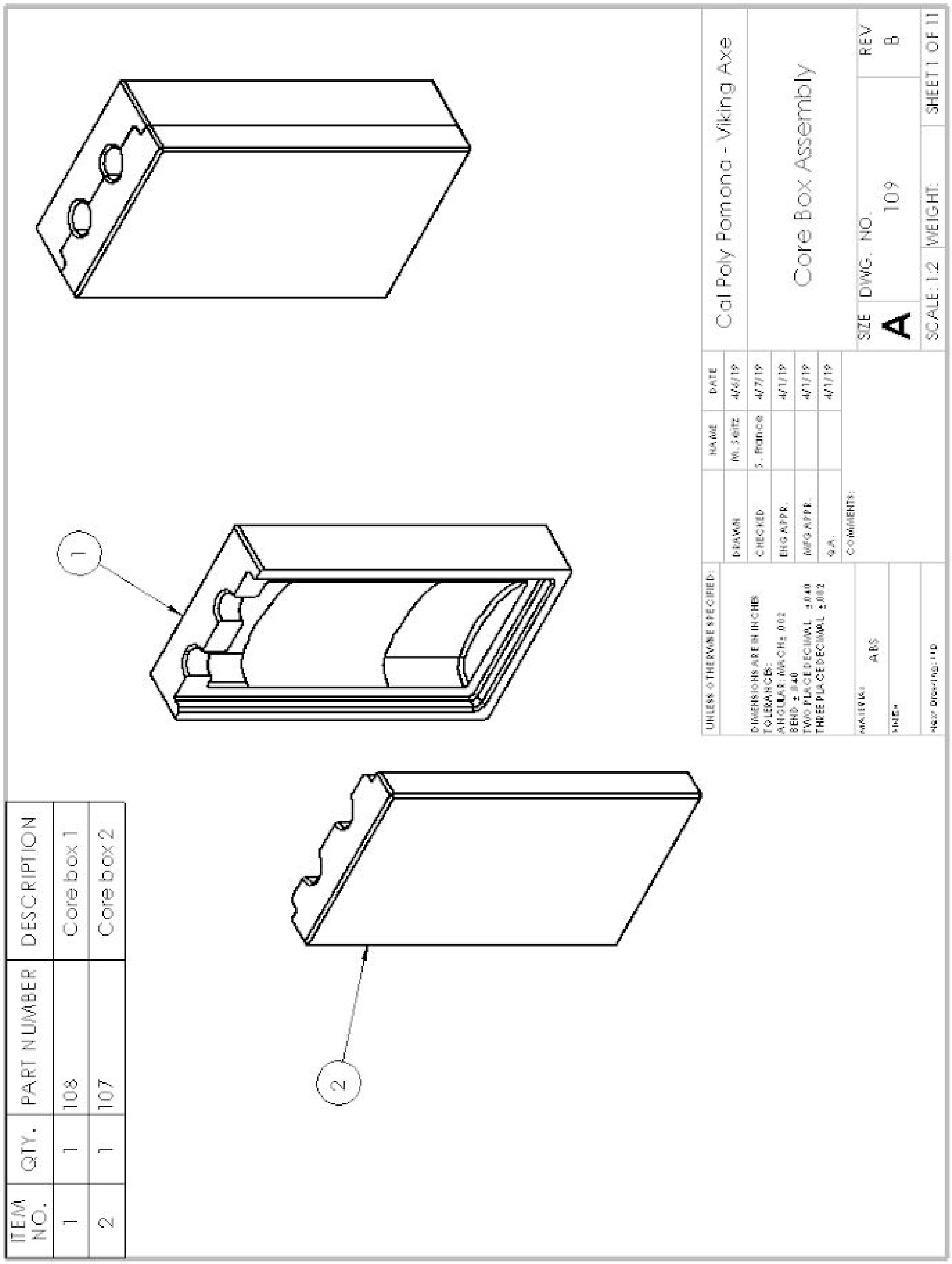

Figure 18: Core Box Assembly

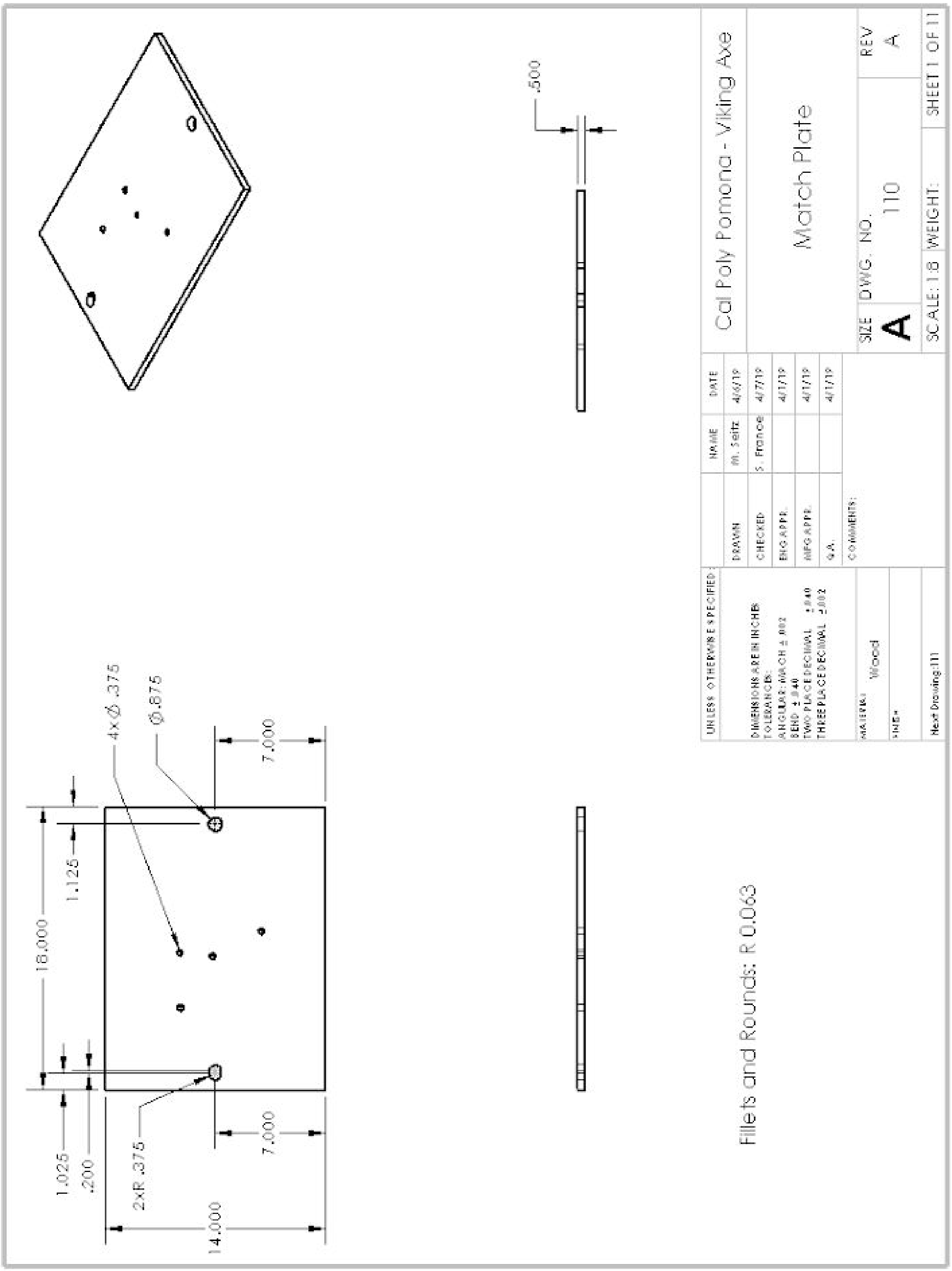

Figure 19: Matchplate

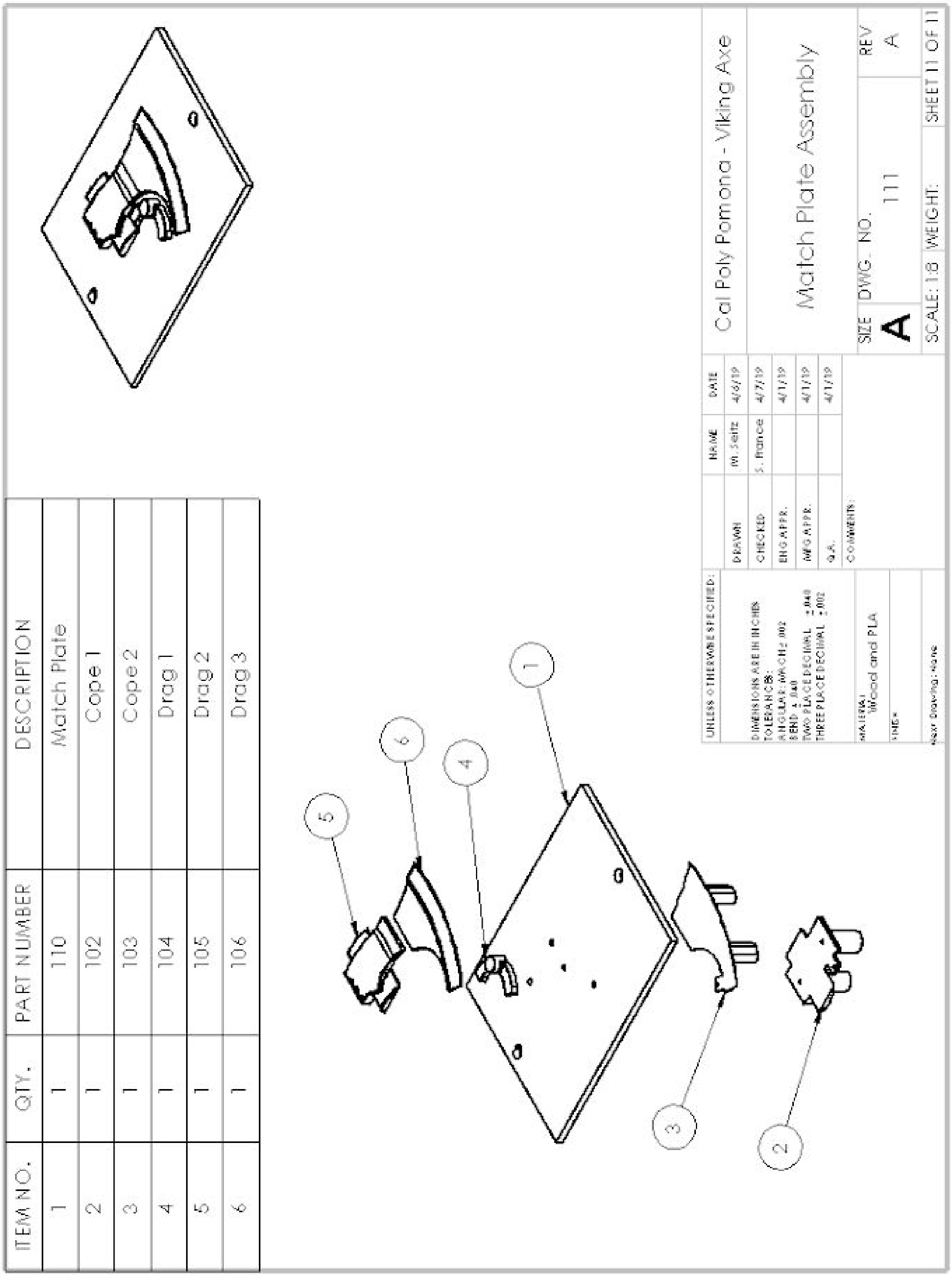

Figure 20: Matchplate Assembly

Once the design for the plate components were finished, the parts were printed out and assembled onto a ½” plywood board. **Figure 21** is a picture showing the pattern components before matchplate assembly, along with the 3D-printed corebox.

Figure 21: 3D printed parts

The board was cut into the size of desired matchplate as can be seen in **Figure 22**. Hole locations were traced out on the board and oversized clearance holes were drilled to allow the pattern components to line up properly as seen in **Figure 23**. Additional holes were milled on each end of the matchplate to properly mate the plate with the flasks. Wood glue was used to combine the pattern components to the plate, and wax filler was used to generate additional fillets as needed around the printed parts as shown in **Figures 24 and 25**. The finished matchplate is shown in **Figure 26**.

Figure 22: Steven, Erick, and Ben cutting the matchplate

Figure 23: Steven and Ben drilling holes into matchplate.

Figure 24: clamping cope and drag patterns for glueing

Figure 25: Clamping cope and drag patterns for glueing

Figure 26: Matchplate with flask on both sides

3.4. Prototyping

In order to prepare for a proper pour in CA6NM, a test pour was done on campus out of aluminium to gauge the functionality of the matchplate. The mold was made by the group using petrobond sand as seen in **Figure 27.** The test mold can be seen in **Figure 28** and **Figure 29**. The cope and drag suffered from a moderate amount of tearout resulting in excessive flash on the casting seen in **Figure 30**. Otherwise, the pour was successful, and would work more success when using furan resin binder at Strategic Materials Corporation.

Figure 27: Packing sand with matchplate on bottom

Figure 28: Mold of cope

Figure 29: Mold of drag with core box placed inside

Figure 30: Prototype aluminum casting

3.5. Production Processing

Strategic Materials Corporation assisted in casting a total of 4 molds. The foundry uses furan resin sand molding to build molds without the need of an individual flask for each mold. The molds and matchplate were sprayed to help the pattern release and prevent burn in and burn on of the sand mold. An open mold sprayed with the refractory coating can be seen in **Figure 31.**

Figure 31: Molds from foundry where steel axes were cast

The foundry assisted us in using an electric arc method to remove the risers and gates from the finished castings**.** Within Solidcast we had simulated the casting process and then designed the gates and risers accordingly to the simulation. However, when the foundry cut off the risers we ran into some issues with shrinkage at the riser contacts. In order to deliver an acceptable product, we welded over the larger porosity issues on the riser contacts. In retrospect, this shrinkage could have been caused by the change in alloy and could be resolved by running simulations and testing with more robust risering.

Once cut, the parts were sent through a heat treatment cycle. The heat treatment cycle that got the properties for our axe consists of Normalizing at 1860 for 2.5 hours and air cooled, and tempering at 1125 for 2.5 hours and air cooled. This resulted with a HRC 28 property with our Viking Axe. Once we received the axe heads, we decided to consult with a couple of metal heat treatment facilities to have the blade of our axe heads hardened, however the facilities we consulted with only had the capabilities to harden the whole entire axe head, in which it would result in having the whole entire axe head lose ductility and impact resistance by a substantial amount.

As for post- processing the use of a sand blaster was used to remove mill scale from the axe head followed by different grits of sand to produce a nice surface finish. The belt sander was implemented to sharpen the blade of the axe as seen in **Figures 32 and 33.**

Figure 32: Belt sander used to shave off mill scale

Figure 33: Ben sanding off mill scale on axe head

4. QUALITY & PERFORMANCE

Table 1 shows the chemical composition of the axe head. All alloy specifications were within the range expected for CA6NM.

Table 1: Chemical Composition

	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**
	%	%	%	%	%	%	%	%
Min						11.5	0.4	3.5
< x > (1)	0.0297	0.397	0.736	0.019	0.008	12.12	0.851	4.06
Max	0.06	1	1	0.04	0.03	14	1	4.5
	Al	**Co**	**Cu**	**Nb**	**Ti**	**V**	**W**	**Pb**
	%	%	%	%	%	%	%	%
Min								
< x > (1)	< 0.001	0.0736	0.219	0.019	0.0034	0.0489	0.0194	< 0.002
Max			0.5			0.05	0.1	
	Sn	**As**	**Ca**	**Se**	**Ta**	**B**	**N**	**Fe**
	%	%	%	%	%	%	%	%
Min								
< x > (1)	0.008	0.0269	0.0003	0.0091	< 0.0200	0.00077	0.0529	81.3
Max								

After the heat treating cycle, the hardness of the axe head (**Figure 34**) was found to be HRC 28. This confirmed that the hardness was within the range expected from the heat treatment cycle.

Figure 34: Post heat treatment hardness testing - HRC 28

A chopping test was performed to test the durability of the the axe. This was done by using it against a 2x4. Our axe was able to withstand the impacts against the wood and after multiple attempts it was able to break through the wood, showing the sharpness of the blade. There was no damage to our cutting edge which further shows the durability of the axe.

The robustness of the axe was seen when it was tested against the 2x4 as mentioned before. If it were used as a weapon it would be able to withstand strong impacts as we acknowledge that when we used it against the 2x4 the grains of the wood making it even harder. The alloy we chose is also corrosive resistant making it able to withstand the outdoor elements that would be encountered in battle.

The shape of our handle is ergonomically designed so that it can easily be grasped and wielded. This was accomplished by the curvature in the handle to provide an easier grip. In addition, the placing of the gripping section was placed lower on the handle so that there could be some leverage when striking the axe thus increasing the striking force. Since the handle is also curved there is less shock to the operator when they strike it and it increases the life of the handle.

We had to make sure that the weight of the axe head was not to much for our handle nor that it would throw off the swinging of the axe. The weight of our axe is approximately 7 pounds and the handle is 36 inches long so they are proportionate to each other. This gives the axe an overall balanced feel. Another aspect that was added to the axe head is that the bottom of the blade does not have a tip so that it can be picked up with more ease. It also makes it safer than those with a sharp tip if the user desires to get a closer grip to the axe head.

5. CONCLUSION

Finally, this Viking Axe Competition allowed us to take the skills we have accrued throughout the years at Cal Poly Pomona and put it to the test. Our mental road map going into this competition was pure excitement, in which we planned and designed our entire axe collectively. We went through several revisions of the axe head, and then we had also considered several different options of steels to utilized. Our initial choice was CA40 Stainless Steel; however, we had a change in direction and made a final decision with CA6NM Stainless Steel. Working closely together we were able to quickly move from the production of the matchplate to casting a test part on campus and finally pouring the final axe head. This competition has been extremely rewarding for the team and were proud of the final product we were able to produce.

We were very grateful to get a real life experience on how to operate, plan, and execute as a group. It was also eye opening for some members within this group to be able to work with a local foundry, Strategic Materials Corp. and see how a Steel Foundry operates. For some members, it would help make a career decision for some of us who could be interested in working in a foundry. In the future, we would look into several alternative forms of casting that would particularly improve our yield. Another difference we would make in the future, would be to test it with a vertical molding process which would allow for more efficient risering and feeding while also potentially increasing our yield as well. Finally, we would also investigate in various different finishing techniques that would produce a better finish while being efficient at getting the finish we desired for the axe.

Figure 35: Project team members with final product

Dr. Dika Handayani, Benjamin Duong, Steven France, Michael Seitz, and Erick Zamora.

Works Cited

Axes. (n.d.). Retrieved April 6, 2019, from https://en.natmus.dk/historical-knowledge/denmark/prehistoric-period-until-1050-ad/the-viking-age/weapons/axes/

Hurstwic: Viking Axe. (n.d.). Retrieved April 6, 2019, from http://www.hurstwic.org/history/articles/manufacturing/text/viking_axe.htm

Schleg, F. P. (2006). Technology of metalcasting. Schaumburg, IL: American Foundry Society.

Steel Founders' Society of America (2004), Supplement 8 High Alloy Data Sheets Corrosion Series. *Steel Casting Handbook.* Retrieved April 6, 2019 From https://www.sfsa.org/publications/hbk/s8.pdf