Cast in Steel 2020 Bowie Knife Competition

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The Knife Design and Manufacturing Process:

Abstract:

The knife design concept was started in early 2020. We wanted a big d-guarded bowie knife with a destructive pommel. For the alloy we wanted a stainless steel so it could avoid oxidation and stay shiny. For the handle we wanted to keep it simple and fit the contour of the steel tang. We also wanted more than one knife, many more... so we decided to design a process to make more than one. A small manufacturing run of around 15 was planned.

Casting Process:

For the casting process we chose investment casting. This process was chose over sand and other alternatives for its ability to produce thin wall and tight tolerance castings and its ability to cast essentially any alloy. A plan was made to manufacture an aluminum wax tool for the knife as well as a supplemental rubber mold for a decorative pommel. These tools would be used to produce wax knives and wax pommels. We wanted to stick to wax because 3d prints can be troublesome to burn out and we wanted wax surface finishes on our castings.

Alloy Selection:

The alloy decided for the knife casting was CA6NM stainless steel. This alloy was suggested by my friend, metallurgist Dr. Roger Lumley for its excellent mechanical properties as well as its corrosion resistance. Below are its chemical composition and mechanical properties of the alloy. The pommel was decided to be cast from aluminum bronze alloy because of its very high corrosion resistance and its hardness when compared to other copper alloys and non-ferrous alloys.

Chemical Composition and Mechanical Properties of CA6NM

C(%)	Si(%)	Mn(%)	P(%)	S(%)	Cr(%)	Ni(%)	Mo(%)
0.05	0.6	0.5-1.0	Max 0.03	Max 0.03	11.5-14.0	3.5-5.5	3.5-5.5

Yield $R_{p0.2}$ (MPa)	Tensile R_m (MPa)	Impact KV/Ku (J)	Elongation A (%)	Reduction in cross section on fracture Z (%)	As-Heat-Treated Condition	Brinell hardness (HBW)
441 (≥)	259 (≥)	44	13	44	Solution and Aging, Annealing, Ausaging, Q+T,etc	414

The Knife Design:

The knife was modeled in SolidWorks. During the design process manufacturability was a constant thought. The design needed to be easy to cast and gate as well as be a robust knife able to withstand and conflict damage. The knife also needed an attachment method for the pommel that would be separately cast. On the next pages renderings of the knife model will be shown.

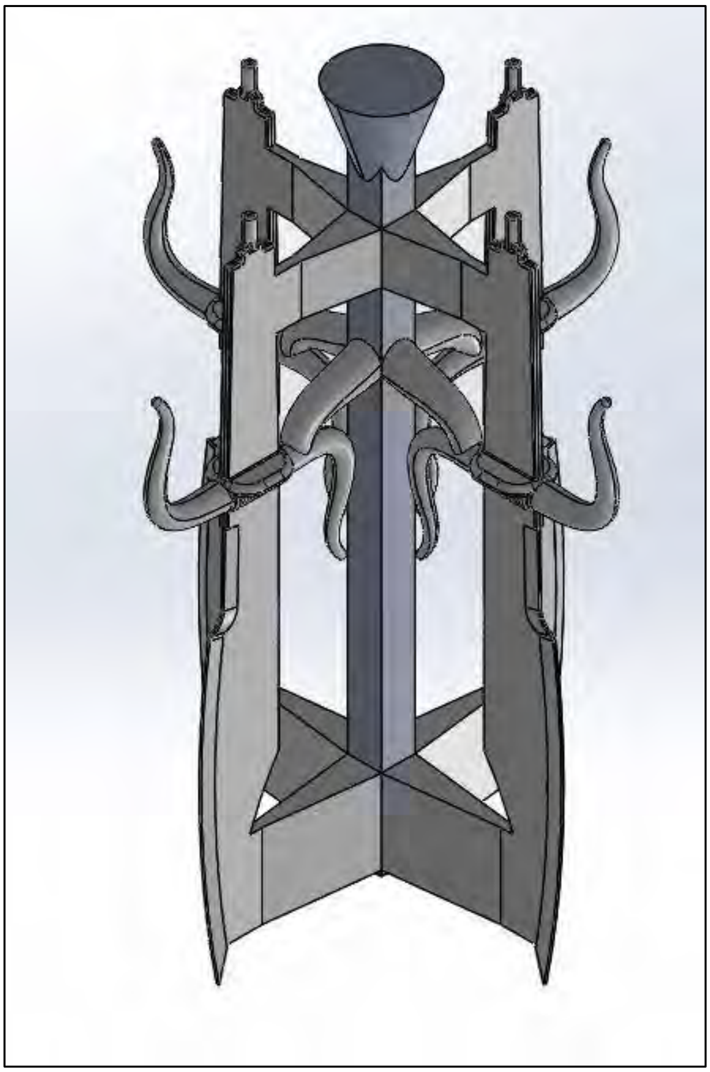
Renderings of the Knife Design:

The design came together nicely. The weapon is 20 inches long from pommel to blade point. The blade itself has 12 inches of cutting edge. The pommel is threaded onto the knife tang by a 5/16 – 18 thread. The handle is made from walnut wood and fastened to the knife casting by 3 .375 press fit brass pins turned on a lathe. This design also could be reproduced multiple times easily for multiple knives.

Rigging the Casting:

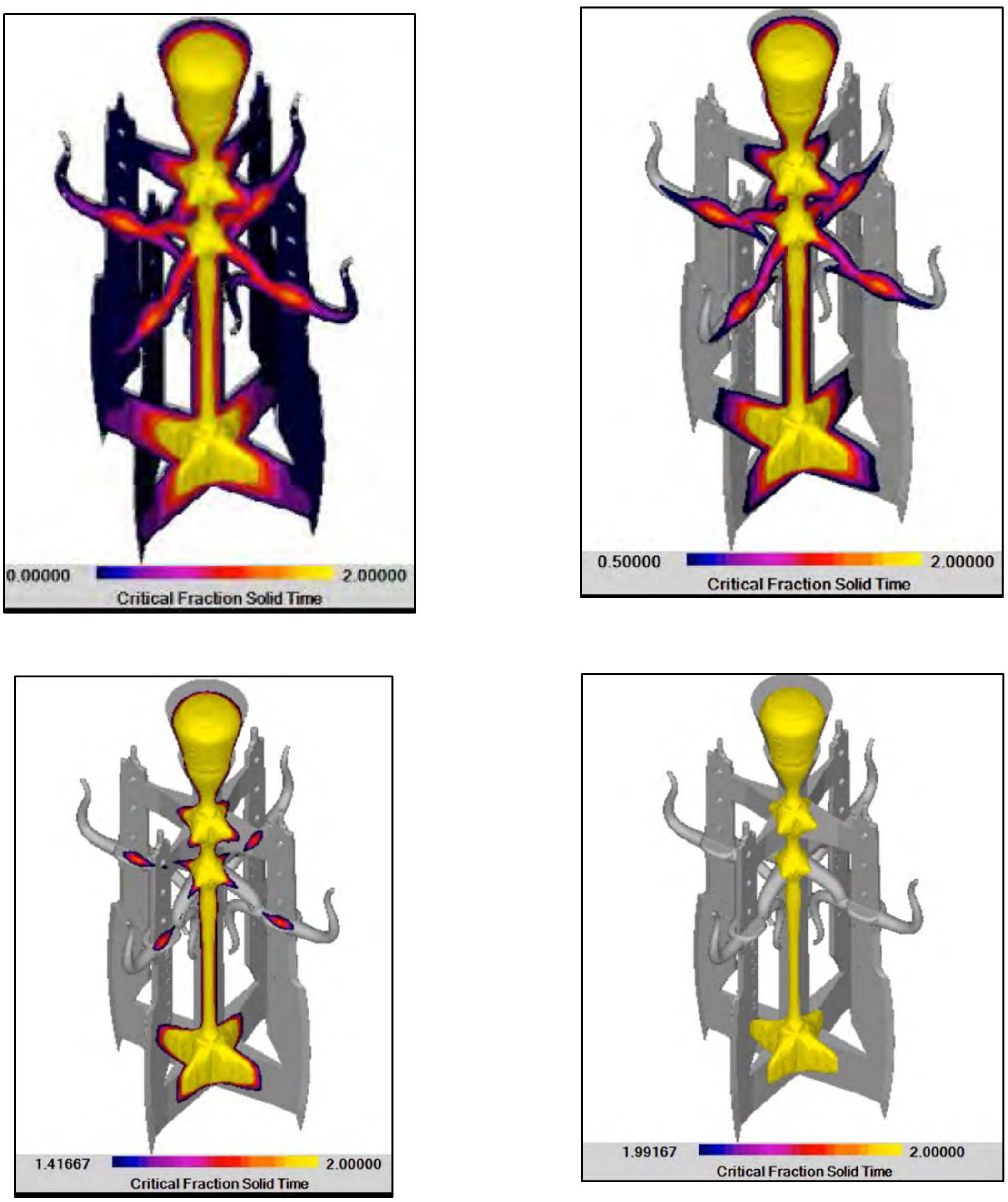
After a couple years in the casting industry rigging other people's castings, I really enjoyed being able to design rigging for a casting I also designed as well. It makes the gating system design flow easily because most of the planning was done in the casting design process. It was decided the best approach would be to gate near the tip of the knife and near the tip of the tang. A large tapered gate was also placed near the central mass of the knife. Gate removal would be simple and minimal after cut off. The gates were also designed to inject into the tool, so when a wax is produced, all 3 gate surfaces are coplanar, and the wax knife can easily be attached to a flat wax sprue. The Treeing method was to use a square sprue and place 4 knives on the tree. We planned on having around 4 to 5 trees worth of knives so around 20. Below are renderings of the planned gating system of 4 on a square sprue.

Cast Orientation Rendering



Simulating the Gating System:

Casting Simulation software was then used to simulate the investment casting process. From previous experience in steel investment castings I thought a 1550 F shell preheat temperature and a 2950 F pour temperature would be sufficient to fill the cavity and produce a sound casting. So, in the simulation software CA6NM was chosen as a casting material, a 3/8 in investment mold was generated around the casting metal, and the temperature of the shell and metal were as stated above. A pour time of six seconds was used for the fill rate and a 1 mm cube mesh was built to model the process. Below is the solidification profile of the gating system generated by the software.

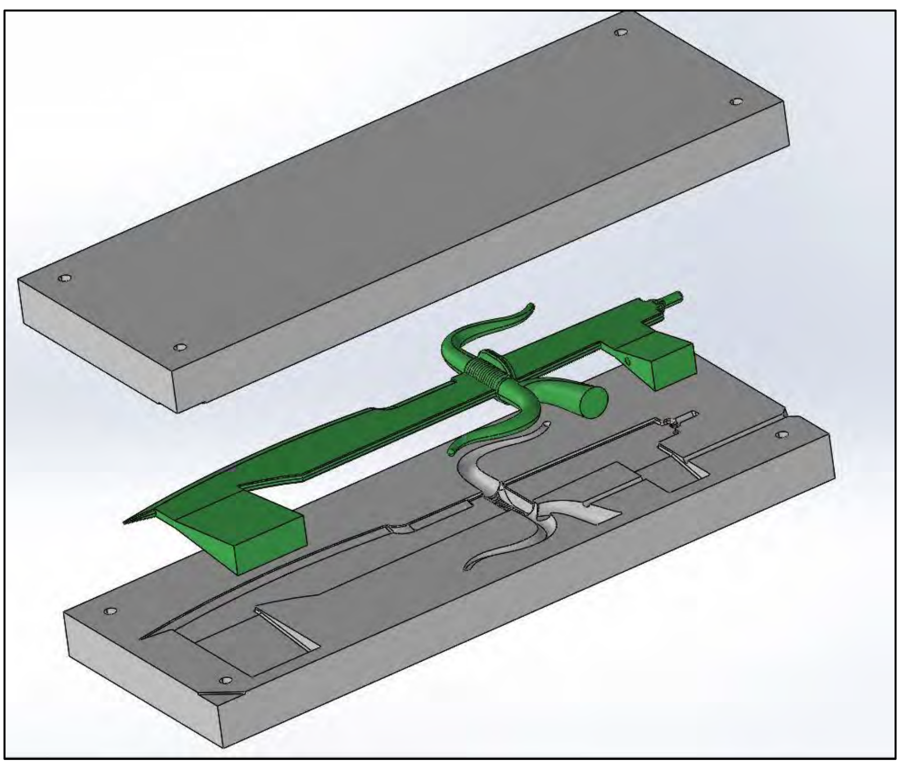


As can be seen from the solidification profile of the gating system there was an isolated mass region in the center of the knife. This was not considered troublesome because the software only predicted 5 percent porosity could show up in that area. This would not hurt the function of the knife and the knives will never be x-rayed to find out if shrinkage porosity exists. Otherwise it appeared the knives would fill in this orientation and I had a gut feeling this would be a proper gating system that would produce sound steel castings. The metal would fill from the bottom at a nice gentle speed keeping head pressure from the sprue by backing up the system with a quick pour time.

Designing Tooling to Produce Wax Patterns:

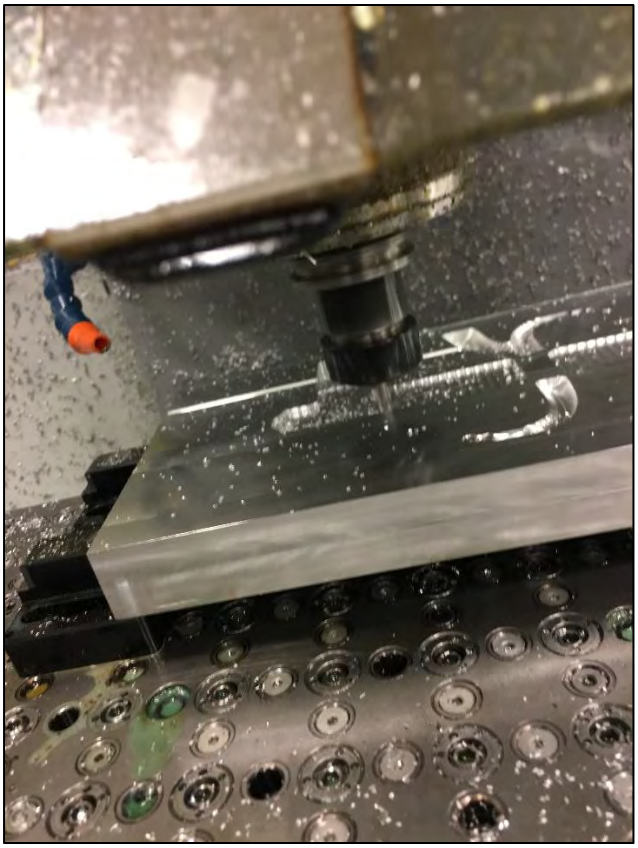
As mentioned, before we wanted to manufacture an aluminum wax tool and a rubber mold for the pommel to produce wax patterns to use as our investment. The wax tool was going to be big and the mold cavity was not a simple CNC program. The tool itself was modeled in SolidWorks. We wanted the knife to be as close to the model as possible so that we could accurately produce the handles and attach the pommel easily. To do this this we applied a wax contraction of 1 percent and a steel contraction of 1.8 percent. So, this meant we cut the tool 2.8 percent bigger to achieve a casting with dimensions as close as possible to the model. One reason we wanted this accuracy was for our tang that we would need to thread with a 5/16 – 18 die. The O.D. needed to be pretty accurate as cast to accept the die optimally. The other reason was because we are engineers. Below is an image of the rendered die design with an injected pattern.

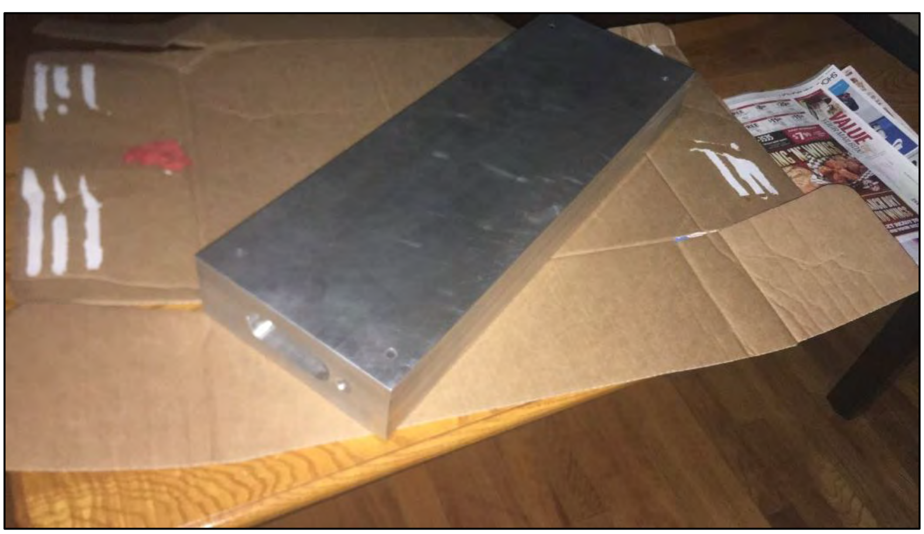
Rendering of Wax Tool



Machining the Knife Tool:

The knife mold was cnc milled and programmed at Pitt State by myself. I used Mastercam to program the mold halves. The mill used was a Haas. Most of the work was done by an 1/8 in ball endmill using scalloping tool paths. Below are some images of the mold being machined and roughed as well as images of the completed die.



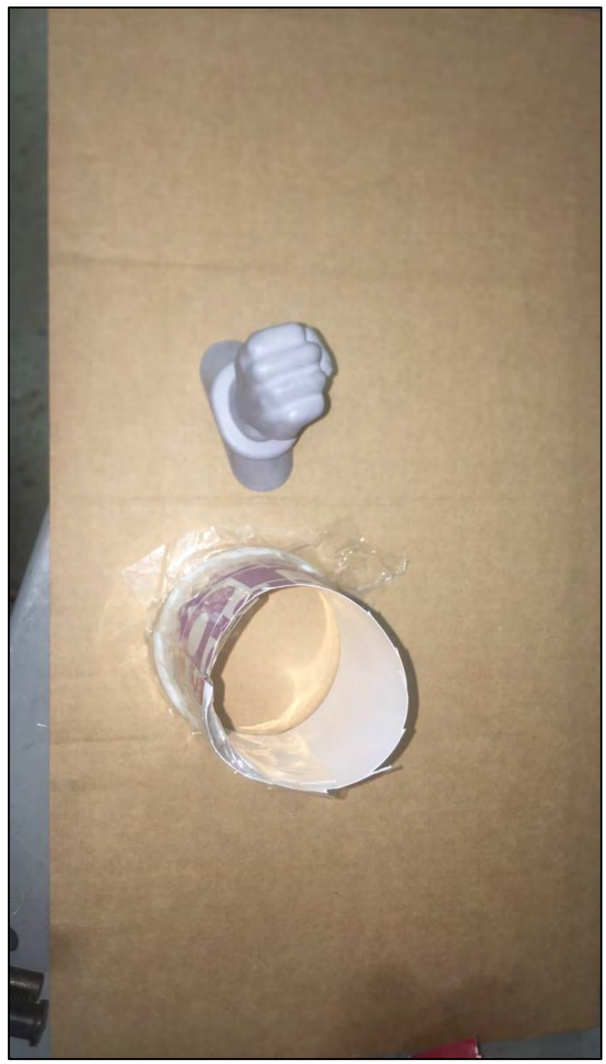



VALUE

Creating the Pommel Mold:

To create the rubber mold for the pommel a model was 3d printed to use as a master to make a mold from. This master was given a 2 percent contraction 1 percent for wax and 1 percent for the aluminum bronze. The 3d print master pattern was then coated with primer and sanded to remove the layer lines of the FDM Process. Below is an image of the mold master and flask which was a McDonalds cup. The pommel was then placed in the flask and mold making silicone was poured in. The flask was then placed in a vacuum chamber to remove any air bubbles. The mold dried overnight. Then it was removed from the flask and a parting line was cut to remove the master pattern.

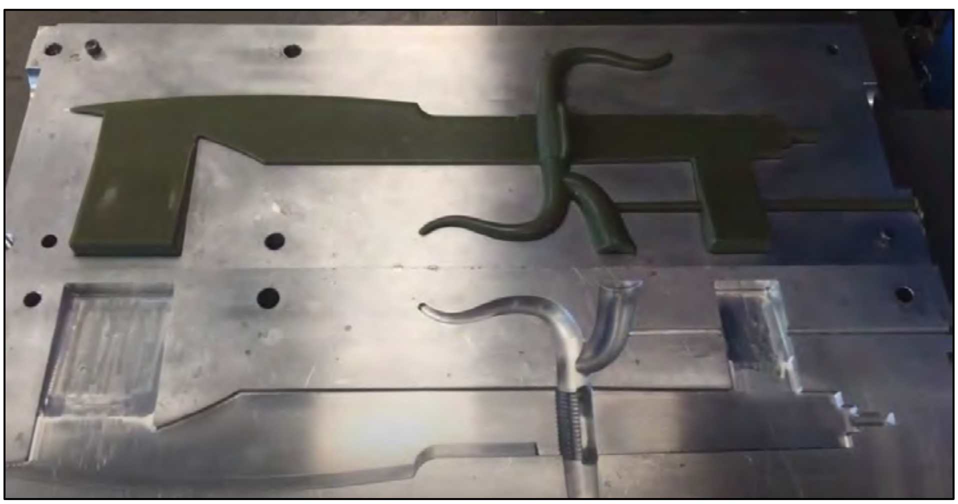
The Master and The Flask



Wax Pattern Creation:

To produce the wax patterns for the knife we used our 12-ton Janke press at the university. When the first pattern was injected it was quickly noticed the machine was too small to completely clamp our die. Wax shot out the end of the die because it was overhanging the machines clamping surface. The fix was to drill and tap 4 holes for ½-13 socket head cap screws to clamp the die together. This worked great and allowed the die to fill with wax under pressure without flashing. Below are pictures of the injected knife wax patterns.

Views of The Wax Injection



The Tool worked great. The average cycle time was around 5 mins. We found keeping our tool on ice greatly reduced the cycle time. Before the ice was implemented the mold would need to remain closed for around 10 mins to let our thick wax gates solidify. This longer wax solidification time also caused wax sink in the gates. The chilled mold really streamlined our injection process.

Waxes Boxed and Ready

Building the Pommel Waxes:

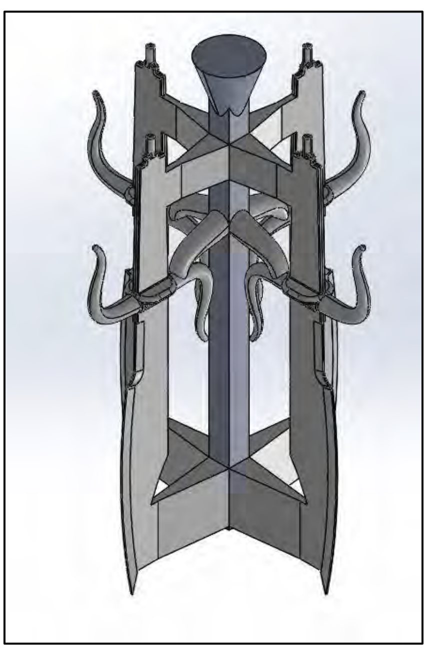
The waxes for the pommels were produced by pouring liquid wax into our rubber silicone mold. This was a long waiting process. It took about 45 mins for the liquid wax to fully solidify in the mold. The top of the mold was kept as flat as possible to allow the pommels to be assembled on a tree easily. The mold was even put in the freezer to increase wax solidification time. Below is an image of a wax fist pattern. 10 pommels were produced.

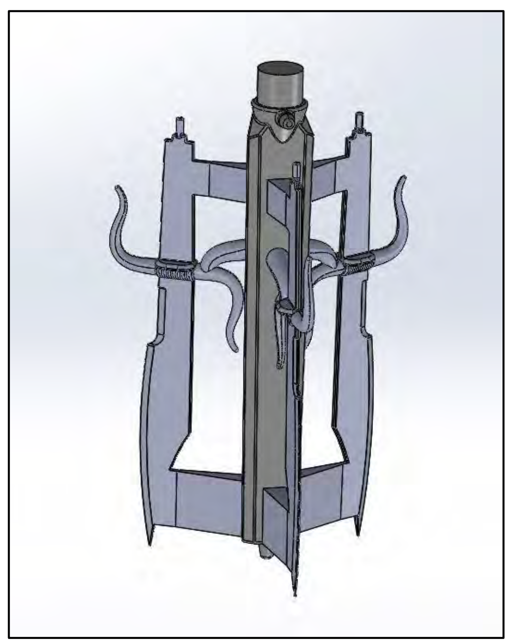
Standing Tall

Working with our Partners:

Before we started the project, we reached out to Abel Ardis and Corey Holt. They both were excited to help us with this project and agreed to pour some knives for us. Abel from American Foundry was in our backyard and we would personally deliver our wax for him to shell build and pour. Abel poured CA6NM knives for us as well as our Aluminum Bronze Pommels. He also completely built the shell for us. Corey from Signicast said we could ship him our tool and they would inject our tool with their paste wax process. He also completely shell built the wax and gave us a little sip of CA6NM.

Below are images of the casting orientations used and our tool filled with Signiacasts's blue wax. At American foundry we treed the knives 4 per tree on a rectangular sprue as seen below on the left. On the right is the orientation cast at SigniaCast. Corey sent me his triangle sprue and I put 3 knives on and returned him the model of how I would like them placed.





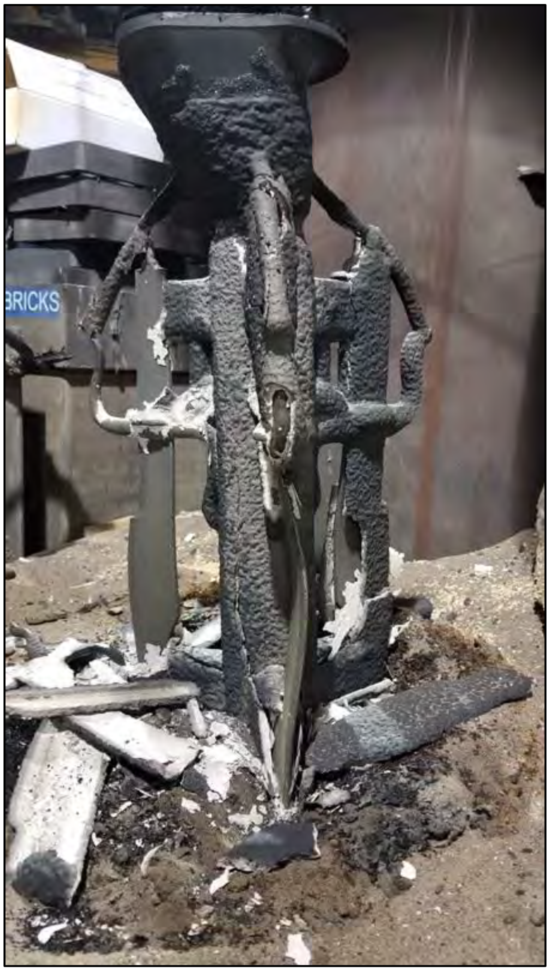
Casting Parameters:

Shell: 1550 F

CA6NM Stainless Steel Pour Temp: 2950 F

Pour Time: 6 seconds

These values were derived from the computer simulations performed. 9 knives were cast at SigniaCast and 12 knives were cast at American Foundry. Only one casting was scrapped in the whole batch of 20. Below are images of the cast knives.

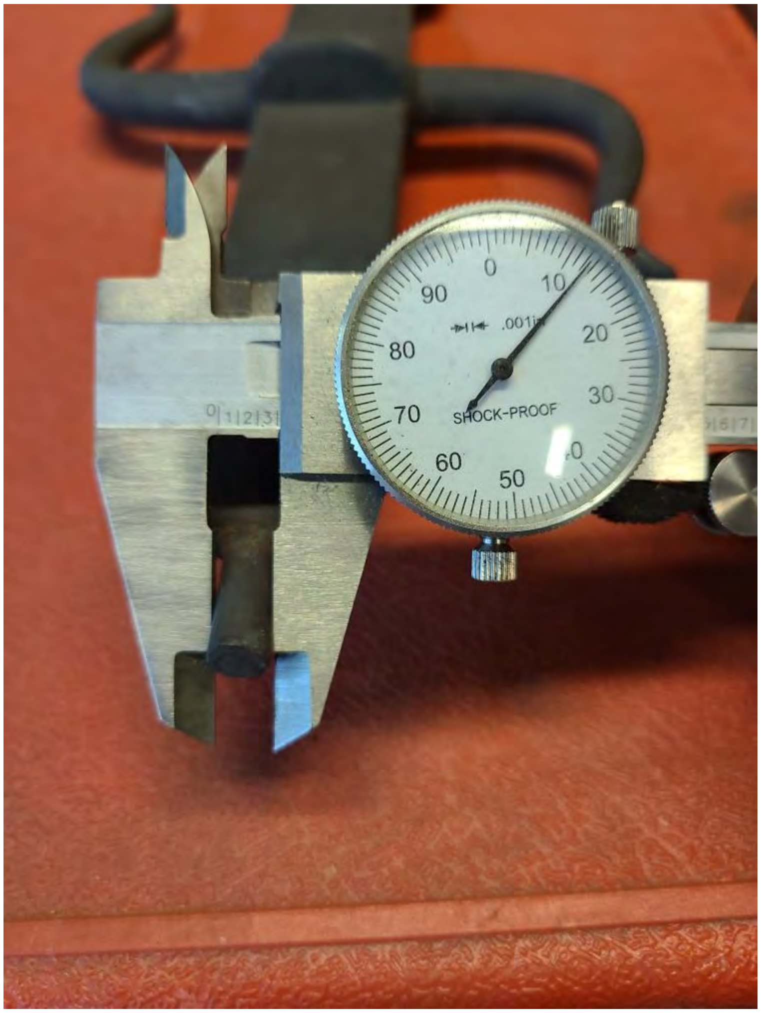


The knives cast at Signiacast had some distortion. Luckily, that was not anything a press could not fix. My hypothesis is the shells broke off or were removed quicker than ideal causing rapid cooling from ambient air, in turn warping the parts severely. Below is an as cast knife.

SigniaCast group was well prepared to straighten warped castings. Below are images of the process they used to straighten the knives.

Analyzing the Castings:

The castings produced at American Foundry had significantly less warpage. 6 of the 11 castings were nearly straight as an arrow. The other 5 castings had anywhere from ¼ in to ½ in of warp. I believe that the castings at American foundry group cooled down slower and in hand produced less warp due to more even cooling. This slower cooling rate could have been caused by their shells being stronger and staying surrounded around the knife longer causing a slower cooling rate. Other than the warpage the castings show no signs of shrinkage porosity or non-fill from both foundries. They all are fully formed castings that appear to be fully sound. Also, the castings are free from ceramic inclusions from both foundries as well. I thought I would at least find a couple embedded ceramic inclusions, but I did not. The casting also dimensionally checked out well. The blade and tang are both .250 in thick and both dimensions were right on the money. The boss on the end of the knife to thread the pommel on also came out great. Below you can see the dimension of .312 showing the casting is very accurate to the model and will easily accept the 5/16-18 thread die. Pictures of the de-gated castings are shown below.



The Lot of 19 Knives

Pommel Casting Results:

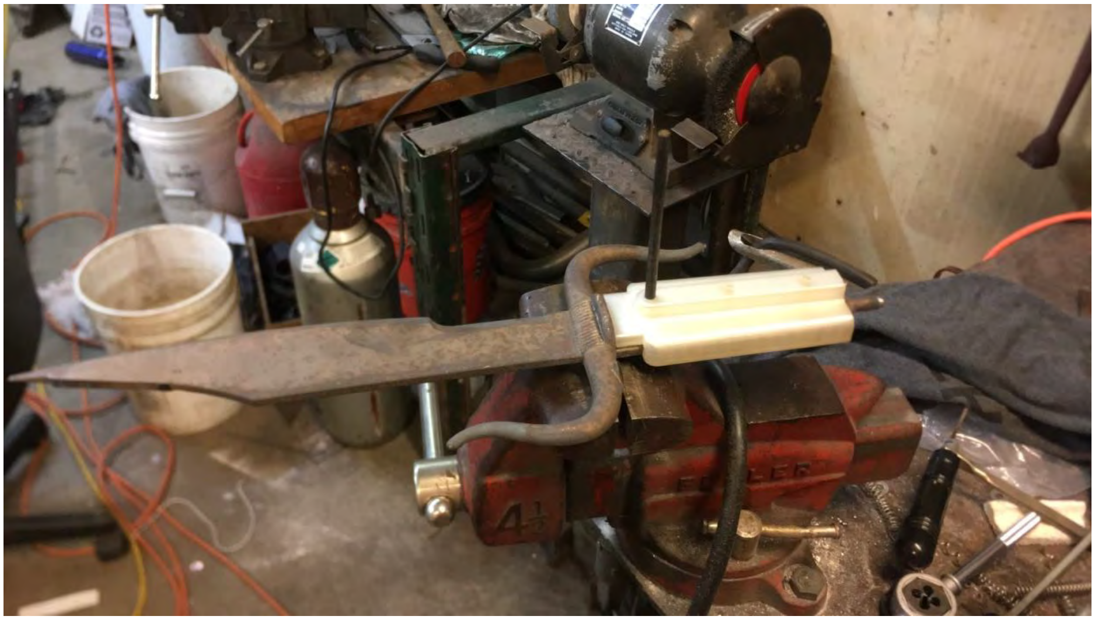
The pommels also turned out great. The wax patterns definitely weren't as crisp as the knives were so the pommels overall had some pits here and there from defects of the rubber mold, like air bubbles and a jagged parting line that showed up on the wax and subsequentially the metal, but overall it was not the fault of the 3d printed master pattern. The master pattern had a smooth finish that could have provided superior wax surface finish. If I was more experienced in the rubber mold making, I imagine the fists surface finish would have been exponentially smoother and free of pits.

Aluminum Bronze Fist

Secondary Machining Operations:

The knife and pommel both needed a couple secondary operations performed. The knife needed a thread tang and three holes for the handle. The Fist needed a 5/16-18 thread and a counter bore. All these operations were performed on a mill or drill press. To locate the handle holes onto the knife a 3d printed fixture was used. The fixture clipped on tight to the knife and allowed a transfer punch to slide in a bushing hole to mark the three holes accurately and quickly. See the fixture in used on the next page.

3D Printed Layout Fixture

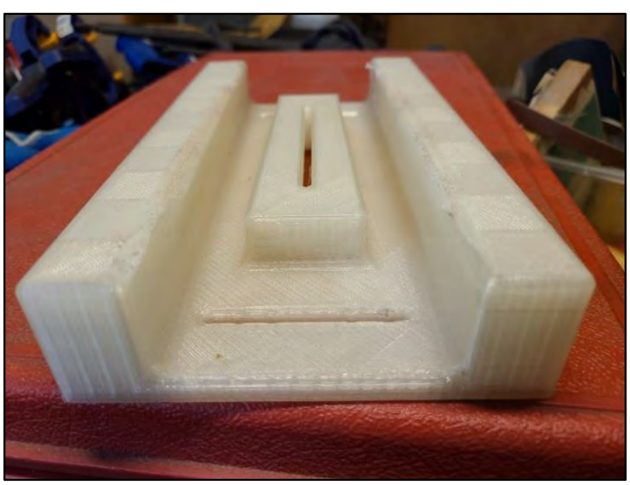


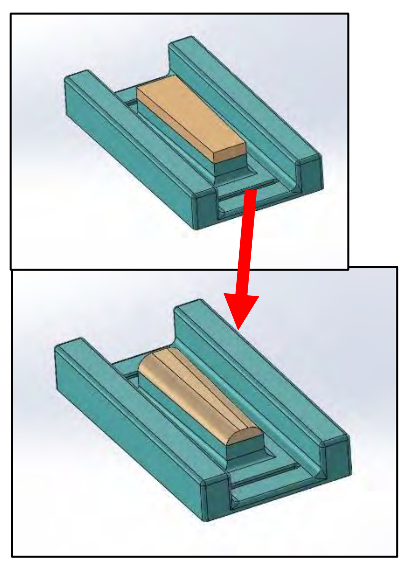
5/16 – 18 Thread on End of Casting

Gating Removed and Counter-Bore and 5/16-18 Thread Machined

Manufacturing the Wood Handle:

The handle was made from walnut. The wood piece was cut from a board planed to the exact thickness as in the model. To put the tapered radius on the handle a router jig was 3D printed. A handle half would be screwed to the fixture. A router with a 1-inch radius bit was then used to follow the two angles of the fixture and put on the complex radius. Below is the 3D printed fixture.





Heat Treatment:

After the holes and threads were put on a few knives we sent them to Kathy Havrvnen at Applied Process to heat treat them. The recipe used was as follows. Heat to 1850 F, air cool to 200 F and then temper at 1100 F remove and air cool to room temperature. The knives appear to be very hard and will skate a file easily. Proper rockwell testing was not available due to our good friend Covid…

Knife Final Assembly:

The first step of assembling the knife was to polish the blade, d-guard, and pommel. After these items were polished the next step was to attach the wood handle. The handle was attached by press fitting brass pins into the wood handle. The handle is held on by press fit only no glue was used to assemble the knife so handles can be changed easily. The handle was then stained, and the knife was sharpened to the best of my ability. Pictures of the assembled knife can be seen below.

Looking in the Mirror

Packaged and Ready to Ship

Conclusion:

Overall, this project has been intense. It was a great deal of work and we had a lot of help along the way. I am very pleased with how the knife turned out. The castings were all sound and fully formed. The wax tool was a massive mold machining learning experience. Also, it was very cool to experiment with silicone molds and wax making for investment casting. The people I talk to are always so confused on how I turned a piece of wax into a massive blade of cast stainless steel. I have many plans for the remaining knives, and I am very excited to experiment with different looks on the knife. I can not thank the foundry members who helped us enough and we will be forever grateful.

Thanks,

Michael Paddock

Thank You Abel Ardis American Foundry

Thank You Corey Holt SigniaCast

Thank You Kathy Havrvnen Applied Process