

University of Pittsburgh at Johnstown
Steel Founders' Society of America

**2020 SFSA Cast In Steel Competition
Technical Report**

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ABSTRACT

This report describes the research, design and material selection criteria, casting process, post casting processes, and quality evaluation criteria for sand casting a Bowie Knife for the 2020 SFSA Cast in Steel Competition. An innovative knife design approach through topological optimization of the cutting edge will be presented along with parametric design of the blade, pommel, and guard of the knife. The decision to cast in a modified 4330 steel with carburization of the cutting edge will be discussed to show a balance between cutting-edge hardness and toughness of the body of the knife. Casting techniques followed and lessons learned will be shown, as well as an overview of the planned work still left to complete after forced schedule changes induced by the COVID-19 coronavirus pandemic.

INTRODUCTION

BOWIE KNIFE HISTORY

While the true origin of the Bowie Knife is debated by historians and knife enthusiasts alike, the legend of the Bowie Knife can be traced back to a brawl in western Mississippi in September of 1827. As the story goes, James Bowie took part in a gruesome fight fielding a large knife, taking on bullet holes and stab wounds, only to emerge victorious despite his numerous injuries. Contributing to the legend of the Bowie Knife is the fact that no one really knows what the knife used by James Bowie looked like. Described as a “large butcher knife” or “peculiar shaped and formidable knife” by contemporary sources, the Bowie Knife of 1827 likely looks nothing like the Bowie Knife of today¹.

Modern Bowie Knives have come to be characterized by their fixed blade, cross guard, and clip point blade². Although this description still leaves much up to interpretation, the team at the University of Pittsburgh at Johnstown (UPJ) decided to base the initial geometry off something similar to the following design found online³.

¹ <https://www.fieldandstream.com/history-bowie-knife/>

² <https://hiconsumption.com/best-bowie-knives/>

³ https://www.swordsknivesanddaggers.com/Gil-Hibben-Legionnaire-Bowie-Knife-II_p_36147.html



FIGURE 1: REFERENCE BOWIE KNIFE FOR INITIAL GEOMETRY SELECTION

SFSA REQUIREMENTS/ EVALUATION

The requirements as outlined by the official competition guidelines for the Cast in Steel Competition include a Bowie Knife with a 9-14 inch blade, integrally cast tang and guard, and a cast pommel that does not need to be integrally cast⁴. No required materials were specified, with the condition that the blade only needs to be cast in steel.

The evaluation of the knives will be similar in process to the show “Forged in Fire” and will likely focus on the strength and durability aspects of the knife. Specific use cases such as chopping, slicing, and puncturing were also mentioned to give an idea of how the knives will be tested.

After reviewing these requirements, several properties were identified by the UPJ team to focus on during the design of its Bowie Knife. Specifically, edge resilience, high toughness, ability to withstand impact without cracking, ability to hold a sharp edge, and a blade geometry that did not concentrate stresses during use were identified. These qualities were used as evaluation criteria later during the physical knife design as well as during design selection of the steel alloy to be used for the knife.

⁴ <https://www.sfsa.org/castinsteel/>

TEAM SCHEDULE AND PROJECT PLANNING

Early on, the team recognized the need to organize its efforts to be successful in this year's competition. For the initial project proposal, a rough schedule with projected project milestones was constructed to guide the team early on.

TABLE 1: INITIAL PROJECT MILESTONES

Finish Date	Task
1/21/20	Research on Bowie Knife and Manufacturing
1/21/20	Finalized Project Plan
2/4/20	Bowie Knife Design and Heat Treatment Plan
2/11/20	Process Plan for casting
2/11/20	Meeting to touch base with Foundry and review bowie knife design
2/18/20	Test Cast
2/25/20	Address issues discovered during test cast
3/10/20	Cast for competition
3/17/20	Forging and Grinding
3/24/20	Quality control evaluation and testing
3/27/20	Finalize Report and Video
3/31/20	Internal review of Report and Video
4/3/20	Deadline for Report, Video, Bowie knife submission

This schedule was later refined with more sub tasks and updated dates into a Gantt chart. A small section of the Gantt chart is included for reference, with the full chart available in the Appendix of this document.

PITT-JOHNSTOWN Cast in Steel Competition Project Schedule

Faculty Advisor: Dr. Serdar Tumkork

Team Members: Alexander Delp, Daniel Kevenk, John Bach, Jonathon Holman, Tanner Badoud

Project Start: Thu, 1/2/2020
 Display Week: 4

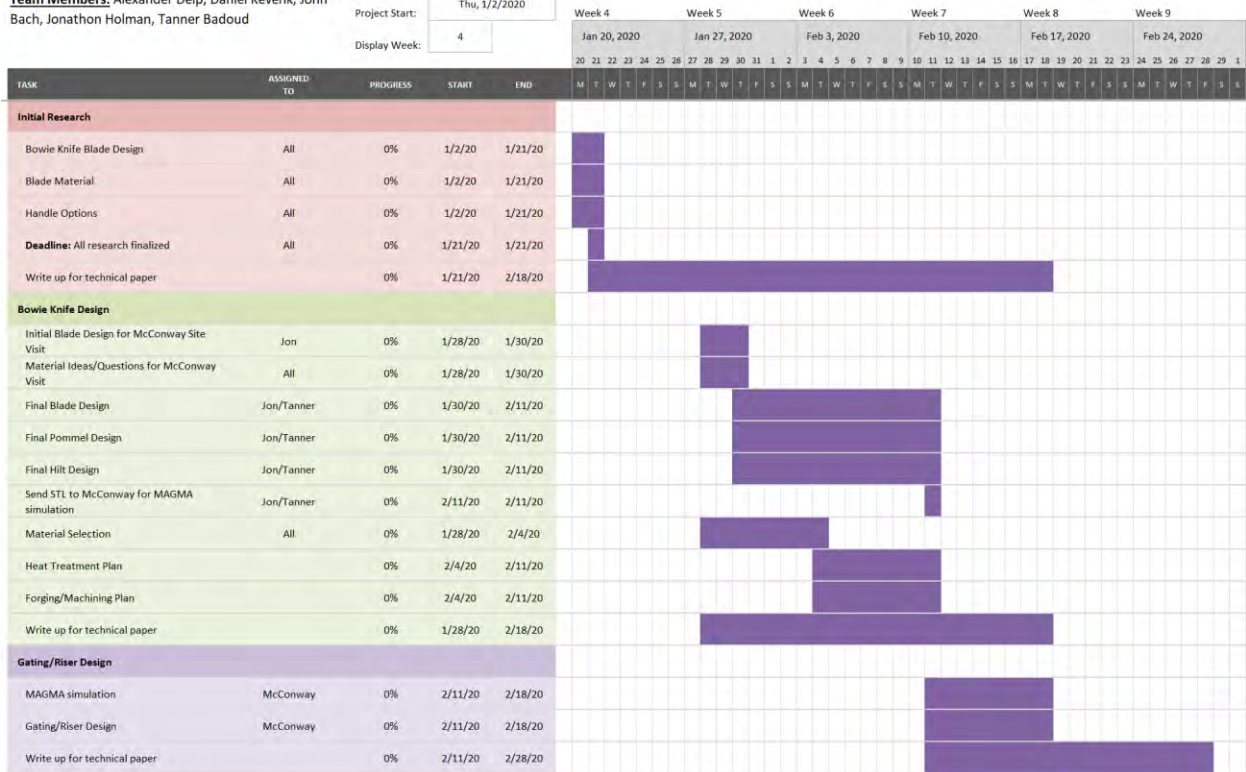


FIGURE 2: SAMPLE PORTION OF UPJ PROJECT SCHEDULE GANTT CHART

Additionally, a time log spreadsheet was created to track team members hours. This helped identify areas where extra time was needed or where tasks could be completed ahead of schedule.

ADAPTED PLANNING DUE TO COVID-19

Due to changes brought on by the COVID-19 coronavirus situation several major adjustments were made to the project schedule followed by the UPJ Team. During the week of March 9th several university wide changes were made affecting extracurricular clubs and activities, including the UPJ Cast in Steel Competition group. Virtually all physical work on the Bowie Knife had to stop due to university policy, and several weeks later state-wide Pennsylvania closures of non-essential businesses ensured work on the Bowie knife would have to wait. Ultimately, these unforeseen

circumstances lead to the UPJ team being unable to fully complete its Bowie knife as initially intended. With the extra time presented by the rescheduling of the competition, the UPJ team chose to focus its efforts on the Technical Paper to fully communicate the knife's design intent, while being unable to showcase the finished product.

BOWIE KNIFE SELECTION CRITERIA

KNIFE DESIGN

From initial design efforts to the final design selection the UPJ team heavily utilized Autodesk Inventor tools to produce an innovative knife shape. After establishing a reference geometry to serve as a starting point for analysis, a full parametric design of the Bowie Knife was completed. With this parametric design it became possible quickly evaluate various design options and gather feedback from all team members.

Once a consensus was reached on critical design features, a topological optimization of the blade geometry was performed to further enhance the shape of the knife. In the topological optimization, an estimated set of loading and boundary conditions was applied to the model to determine the optimal geometry to maximize mechanical behavior. The results of one round of analysis can be seen below.

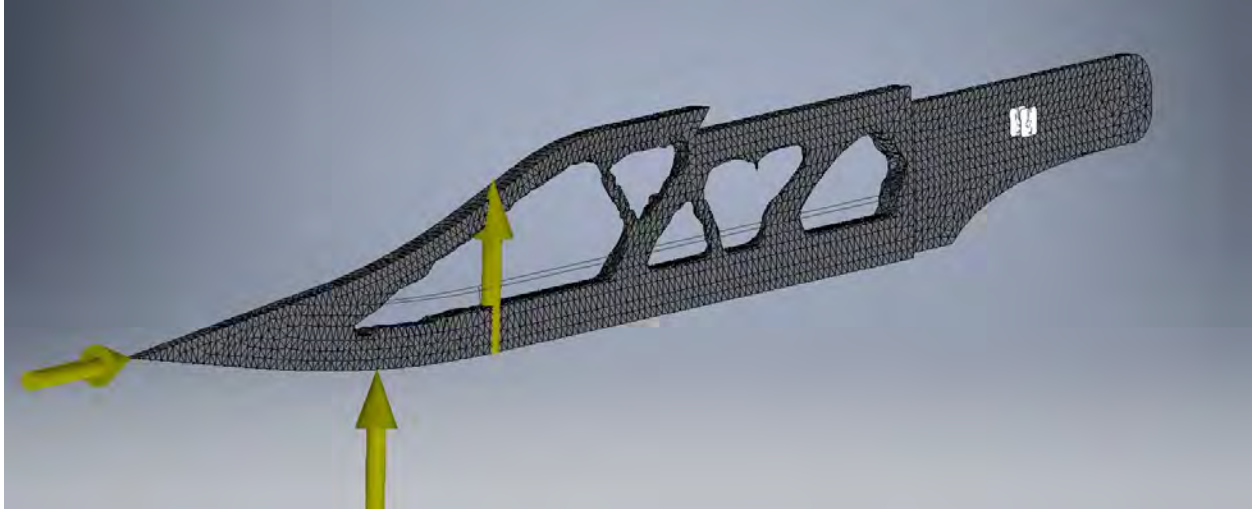


FIGURE 3: END RESULT FROM ONE ITERATION OF TOPOLOGICAL OPTIMIZATION OF THE BOWIE KNIFE

As can be seen from the above figure, the topological optimization identified a unique shape that helped inform future design configurations. The main purpose of the optimization was to determine the most critical base structure of the knife. Several iterations of this test were performed so a safe assumption could be made to what portions of the knife needed to be the strongest. This information was useful in the later determination that carburizing the blade was in the best interest of the finished project.

After finalizing the Bowie Knife design several models were 3D printed to be used in the pattern for casting. A finalized model can be seen below. The printing process was handled by two of the team members. It was ideal to print the gating systems and the knife in the largest portions possible to avoid defects and creases where parts would need to be attached together. To avoid this, a purpose-built large format printer was utilized to print the components of the knife in one large piece, and the gating system in several large pieces so gating simulations would be as close to ideal as possible.

POMMEL DESIGN

For the pommel, a geometric shape was desired, but in keeping with the rest of the knife, a more organic structure was desirable. To accomplish this, the design was created as a boundary driven 3D sketch. All the surfaces were confined with mesh patches, essentially a confined plane, which were then stitched together with the rest of the knife to create a more organic flow to the handle. This allowed for the base shape, a half dodecahedron, to flow evenly and create a more ergonomic shape in the hand while remaining aesthetically pleasing. Several base shapes and offsets from center were design while remaining aesthetically pleasing. Several base shapes and offsets from center were design and rapidly prototyped until the pommel felt both comfortable in the hand and improved grip.

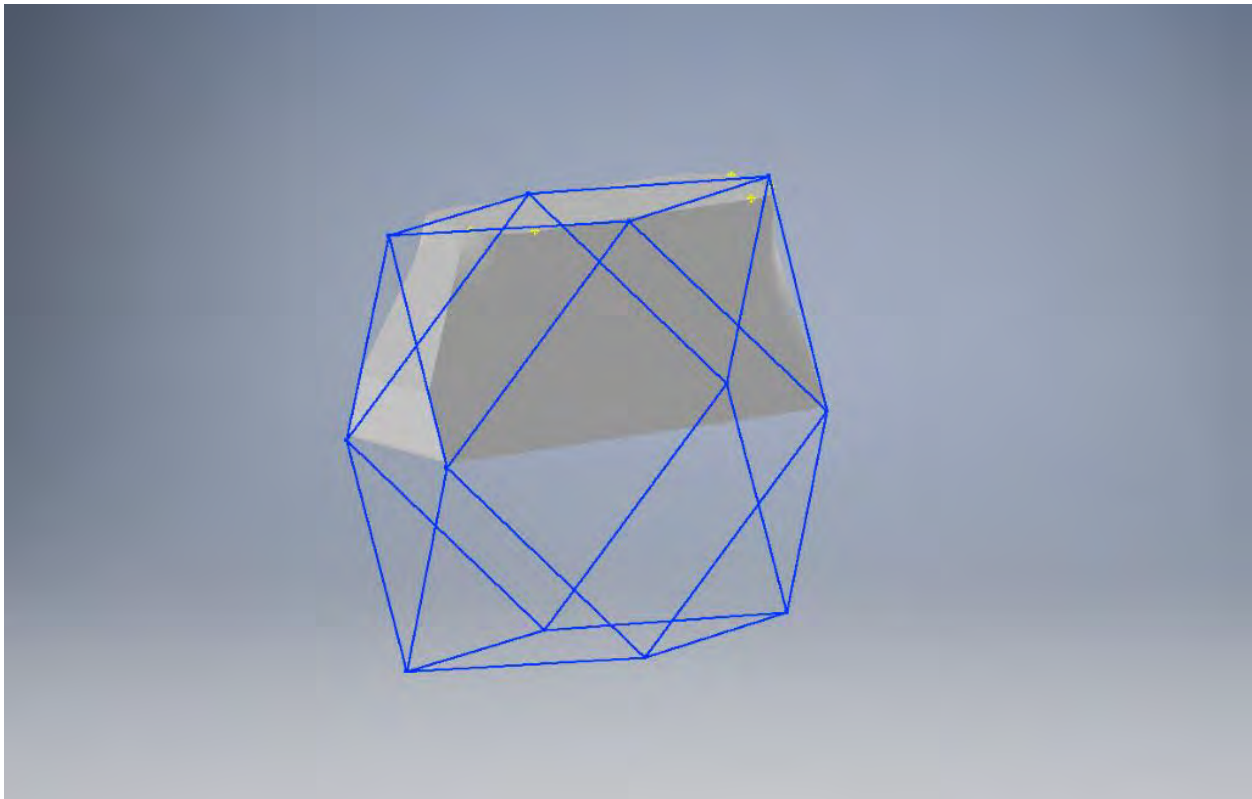


FIGURE 4: POMMEL DESIGN

HANDLE DESIGN

To create a comfortable and sturdy handle, the feel of many types of commercially available handles were evaluated and analyzed. Specifically, other knives, saws, and even sports

equipment like hockey sticks were investigated to better understand functional ergonomic grips.

The contour of a hockey stick was evaluated to be highly functional for directional grip, although it lacked the comfort of several other potential options. To circumvent this issue, the directional profile was created with a protrusion to fit the cup of the palm.

The handle attachment design intent was to pin the handle to the knife with two rivets, placed within the profile of the handle.

ITERATIVE DESIGN

A few different designs were done to test balance, grip ergonomics, and look of the knife. The model was split in half to make one half of the knife for the cope and drag. By utilizing parametric design features on the knife, the surrounding subcomponents could be completely overhauled without making it incompatible with the rest of the knife assembly. This allowed for rapid prototyping for ergonomics in the handle and pommel without needing to strictly design them with tight tolerances for the knife.

The only notable design changes that occurred through the process were aesthetic and ergonomic changes of the pommel and handle. Another notable change was the decision to shift the guard back to allow for a more comfortable balance of the knife.

DESIGN CONSIDERATIONS FOR PRINTING

There were a few advantages that were taken advantage of by using an additive manufacturing process to create the patterns with. The knife halves were printed with settings optimized for high quality, to reduce required post processing. The layer height of the print was reduced to allow for higher resolution on any slopes and to help reduce layer line visibility.

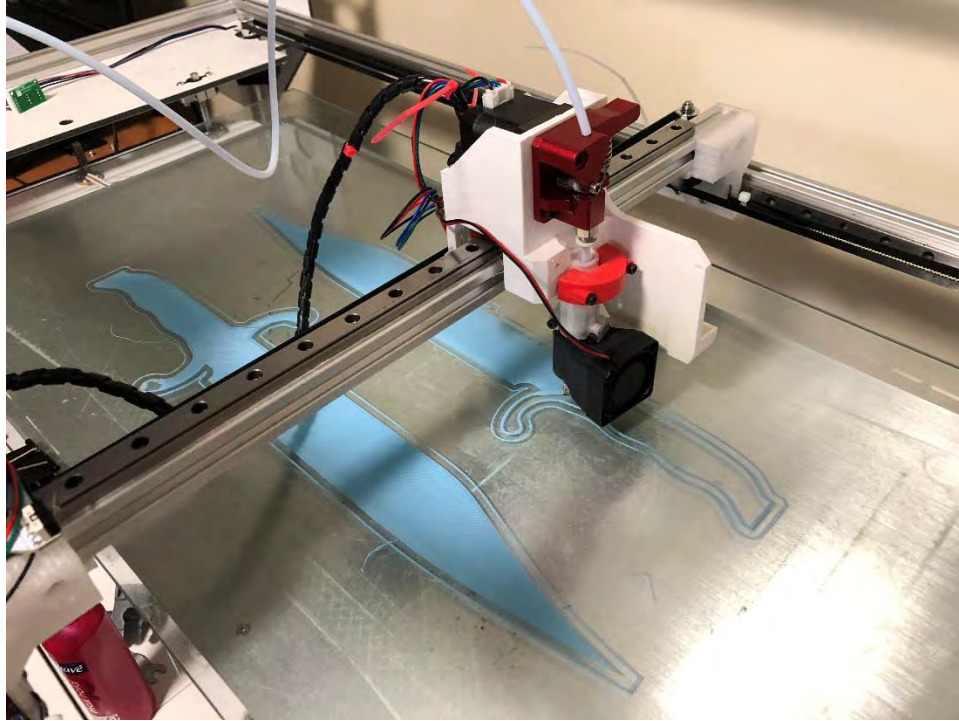


FIGURE 5: BOWIE KNIFE PATTERN MID 3D PRINT



FIGURE 6: FINISHED BOWIE KNIFE PATTERN

MATERIAL SELECTION

When deciding what material to use the team investigated several different options based off the previously noted desired properties including edge resilience, high toughness, ability to withstand impact without cracking, and ability to hold a sharp edge.

Initial research into steels for the Bowie Knife yielded several options including high carbon steels, such as a spring steel or tool steel, as well as lower carbon steels with a proper heat treat cycle to achieve a high hardness for edge retention. From these initial options, 3 finalist candidates were chosen as potential candidates: 1095 carbon steel, D2 tool steel, and a slightly modified 4330 alloy, a specialty of McConway and Torley, the UPJ team's industry partner.

Property data for 1095 Carbon Steel⁵:

TABLE 2: 1095 CARBON STEEL MATERIAL COMPOSITION

Fe	C	S	P	Mn
98.38-98.8%	.90-1.03%	< .05%	< .04%	.30-.50%

TABLE 3: 1095 CARBON STEEL SELECT MECHANICAL PROPERTY DATA

Properties	Metric	Imperial
Tensile Strength	685 MPa	99400 psi
Yield Strength	525 MPa	76100 psi
Elastic Modulus	190-210 GPa	27557-30458 ksi
Hardness, Brinell	197	197
Hardness, Knoop	219	219
Hardness, Rockwell B	92	92

Property Data for D2 Tool Steel⁶⁷:

TABLE 4: D2 TOOL STEEL MATERIAL COMPOSITION

Fe	C	Si	Cr	Mo	V
85.50%	1.50%	.30%	12.00%	.80%	.90%

⁵ <https://www.azom.com/article.aspx?ArticleID=6561>

⁶ <https://www.azom.com/article.aspx?ArticleID=6214>

⁷ <https://www.steelexpress.co.uk/toolsteel/D2-Steel-properties.html>

TABLE 5: D2 TOOL STEEL SELECT MECHANICAL PROPERTY DATA

Properties	Metric	Imperial
Elastic Modulus	190-210 GPa	27557-30458 ksi
Hardness, Knoop	769	769
Hardness, Rockwell C	62	62

Property Data for 4330⁸:

TABLE 6: 4330 STEEL MATERIAL COMPOSITION

Fe	Ni	Mn	Si	Cr	Mo	C
95.3-98.1%	1-1.5%	<1.0%	<.80%	.40-.60%	.30-.50%	.20-.30%

TABLE 7: 4330 STEEL SELECT MECHANICAL PROPERTIES

Properties	Metric	Imperial
Tensile Strength	>860 MPa	>125000 psi
Yield Strength	>690 MPa	>100000 psi
Hardness, Brinell	285	285

From these candidate alloys some comparisons were made to select the final steel. Starting off by comparing carbon content, the D2 tool steel holds a significant lead over the 1095 and 4330, with carbon content 1.5% vs .95% and .25 % respectively. This higher carbon content aligns itself toward a higher edge resilience but corresponds to an increase in probability to crack on impact. So, while a D2 steel would have excellent edge retention, it would likely be too brittle and unable to stand up to the necessary wear and tear of a use cycle of a Bowie Knife.

⁸ <https://www.azom.com/article.aspx?ArticleID=6670>

While considering toughness, an advantage can be given to the 4330-candidate steel for its higher yield strength. Additionally, since 4330 has the lowest carbon content, it follows that it would be the most ductile and exhibit superior impact absorption characteristics.

Finally, along a consideration of hardness, the candidate steels ranked (from hardest to softest) D2, 4330, 1095. With a Rockwell C hardness of 62, the D2 steel had a significantly higher hardness than the 4330 or 1095. Comparatively the 4330 and 1095 were much closer together at 285 and 197 on the Brinell scale respectively.

Considering all these factors, the UPJ team made the initial decision to go with the modified 4330 steel because it seems to provide a balance of all the characteristics the team was looking for. After meeting and discussing potential material options with McConway and Torley a unique idea was had for a further modification to the cast knife involving carburization of the cutting edge of the knife to a higher carbon content near .80%, closer to that of the 1095 alloy. In this configuration, a 4330 base alloy would present its superior performance characteristics for withstanding impact, while also gaining the edge retention features of a higher carbon content alloy.

This carburization concept seemed to provide the best combination of material characteristics, so it became the final material selection.

CASTING DESIGN

GATING SYSTEM DESIGN

To aid in the design of the gating system for casting, MAGMASOFT simulation software was utilized. The initial design (left image) v01 was fed with the parting line of the pattern vertical. This design created some potential solidity issues, but also showed concerns filling the cavity

completely. The second version, v02 was simulated filling through the large section in the hilt. Both the solidity results and the potential porosity within the cavity improved.

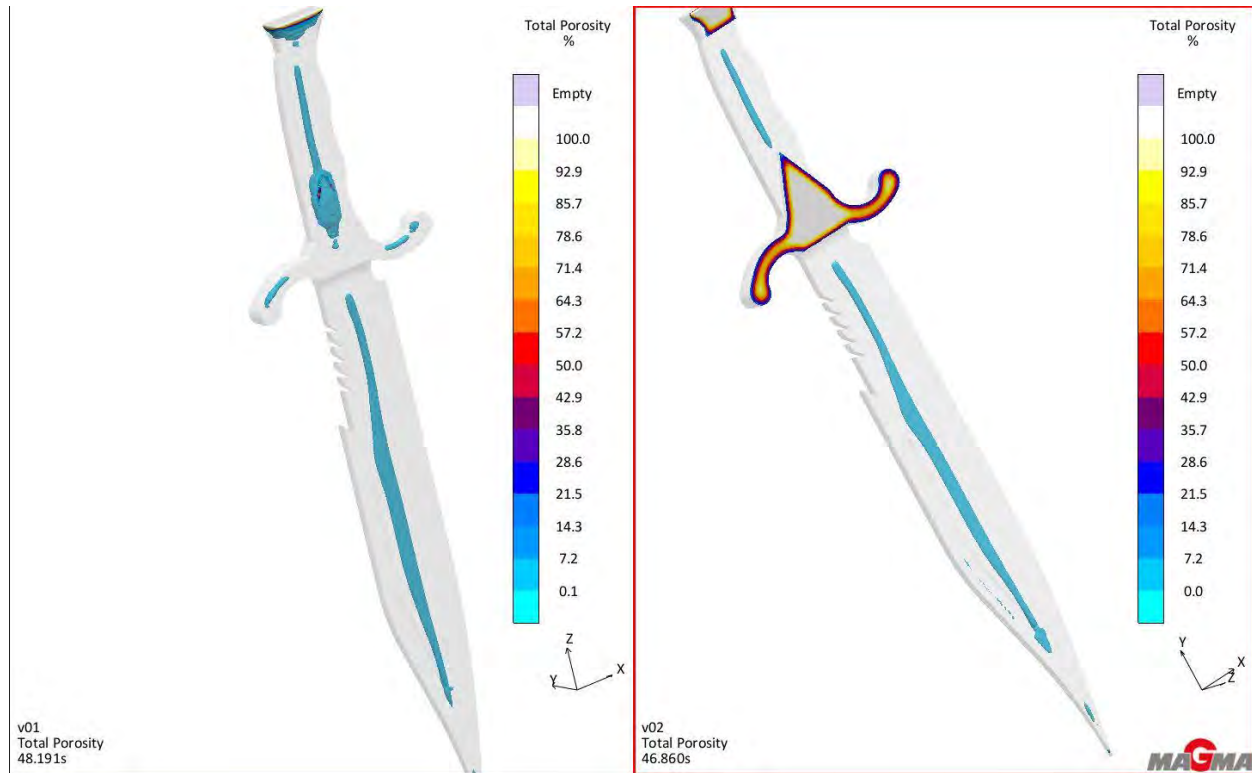


FIGURE 7: MAGMASOFT SIMULATION RESULTS FOR BOWIE KNIFE CASTING

The initial gating configuration produced the concerns listed above, but also created a potential problem when pouring the castings in a production heat at McConway. The nozzle feeding the castings created such high velocity and a large volume of metal that the reduction in gating and volume control had to be a lot more radical than preferred.

The final gating system design can be seen below.

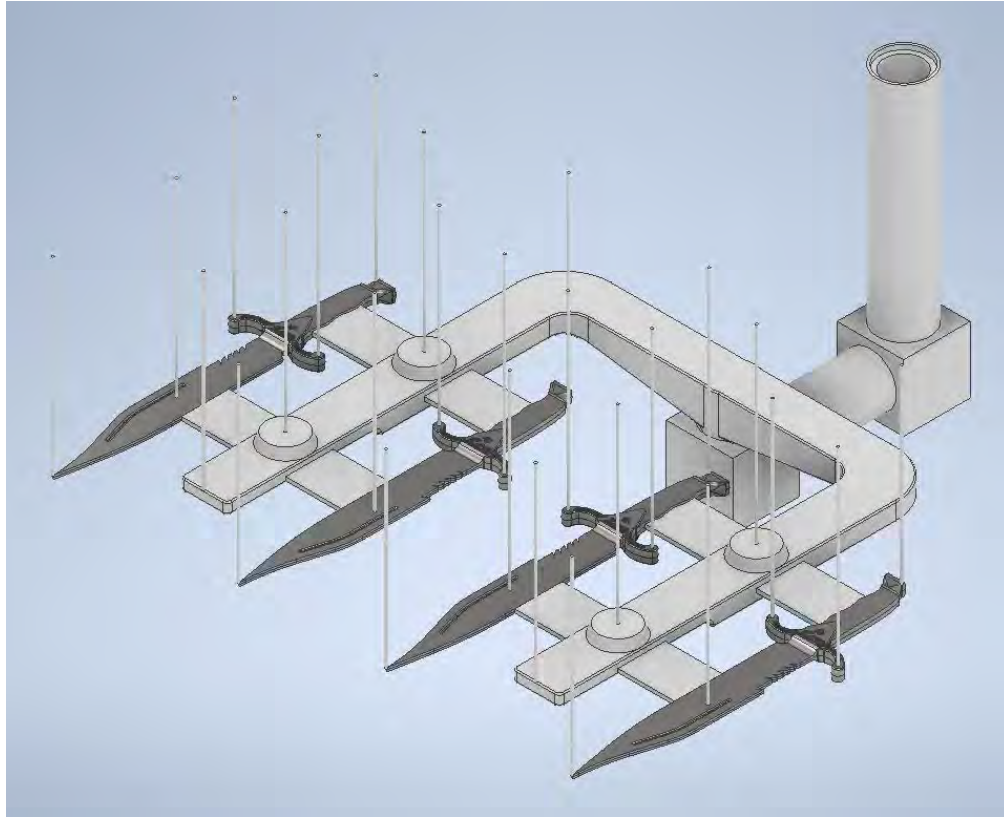


FIGURE 8: FINALIZED GATING SYSTEM DESIGN

Using a modified sprue well from available ceramic gating (2.5 inch) in partnership with the conical section of the gating helped to reduce some of the turbulence in the metal stream. Using a 4 on pattern with runner extensions feeding the blade portion of the knife helped to normalize the velocity. Understanding that a higher velocity is beneficial, the Magma simulation helped to find a balance between high velocity and managed turbulence that still produced a casting with low porosity. After seeing the result of physically pouring the castings, some changes with the pouring temperature and fluctuating that in the magma simulations would have been beneficial.

MOLD PREPARATION AND MOLDING

PATTERN MAKING

FDM 3D printing was the primary manufacturing method for the components of the pattern for casting. After all design work was completed the team printed out 4 sets of knife models and the gating system impressions for making the mold. The completed 3D printed pattern can be seen below.

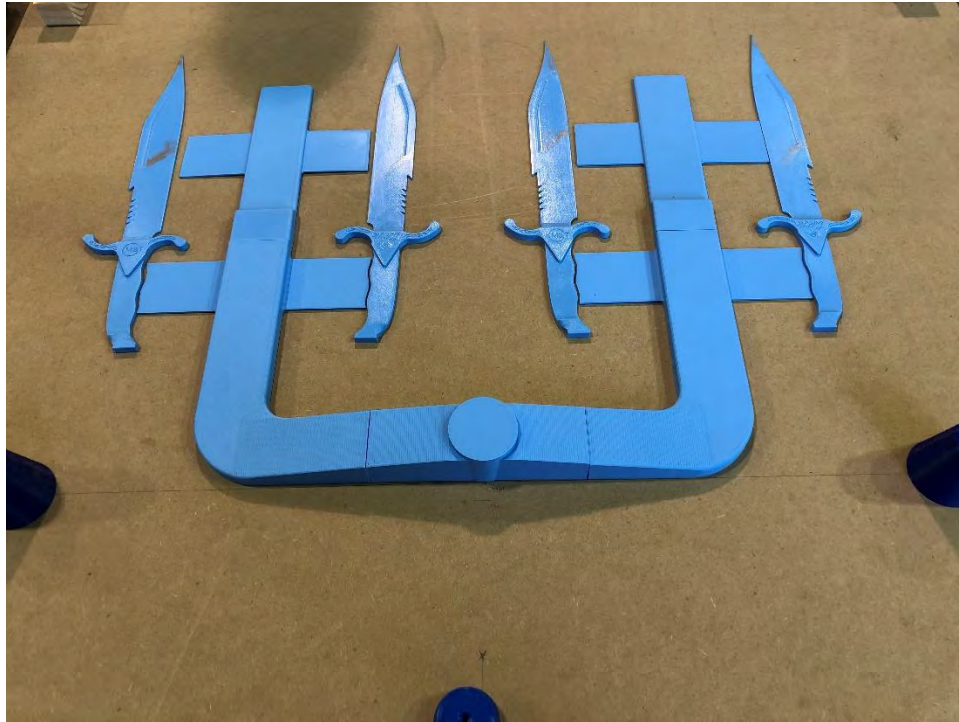


FIGURE 9: COMPLETED 3DPRINTED PATTERN

PRINT POSTPROCESSING

To achieve a smooth surface finish for more desirable results, several postprocessing steps needed to be performed. Although the surface quality was able to be improved by optimizing print settings for detail and sacrificing time, the surface was not as smooth as desired. To reduce the appearance of layer lines, the surface of the print was first sanded with multiple grits. Once complete, any large defects and gaps were filled with bondo and smoothed over. The pieces were then finished

with several coats of polyurethane to fill any small defects and layer lines. A final sanding was performed, and the components were ready for the molds.

MOLD MAKING

The mold making process began by cutting out a flat base for the mold sand to conform to. Then, the layout of the pattern was mapped out so that the two halves will line up properly. The pattern needed to be secured to the flat plate to ensure that nothing shifted during compaction of the sand and the stripping of the molds. When stripping the first molds both cope and drag, there were a few issues with the adhesive delaminating the MDF board that was used as a plate. To avoid this for the other molds, screws and stronger adhesives were used.



FIGURE 10: INSTALATION OF 3D PRINTED PATTERN TO MOLD PLATE

The connections between the parts were then sealed with putty and epoxy to limit any modifications needed on the completed molds prior to closing.



FIGURE 11: INSTALATION OF PUTTY ANDEXPOXY ON PATTERN TO SEAL GAPS

Once the pattern was aligned perfectly and secured in place, a box to hold in the sand was made. This box was made from plywood and supportive 2x4's braced behind the plywood. The box and the base were then mated together. The risers were then placed in along with the pipes used for transportation.



FIGURE 12: MOLD SETUP PRIOR TO ADDING SAND

Before adding sand to the cope and drag, an alcohol-based pattern release agent was added to allow for the sand and pattern to separate properly. Next, the sand was filled into the box and compacted firmly to conform to the mold as accurately as possible.



FIGURE 13: MOLDHALF PACKED WITH SAND

Lastly, the box and pattern were removed from the sand completing one half of the mold. The same process was followed for the other half, ensuring that the two halves lined up properly. One issue experienced during the packing process was during the moving of one mold. Sand was not given enough time to cure and fell through the bottom of the mold when it was moved. More time was given before moving future molds. Using work time and strip time tests would have avoided this mistake, but it was a learning opportunity and all the others worked well.

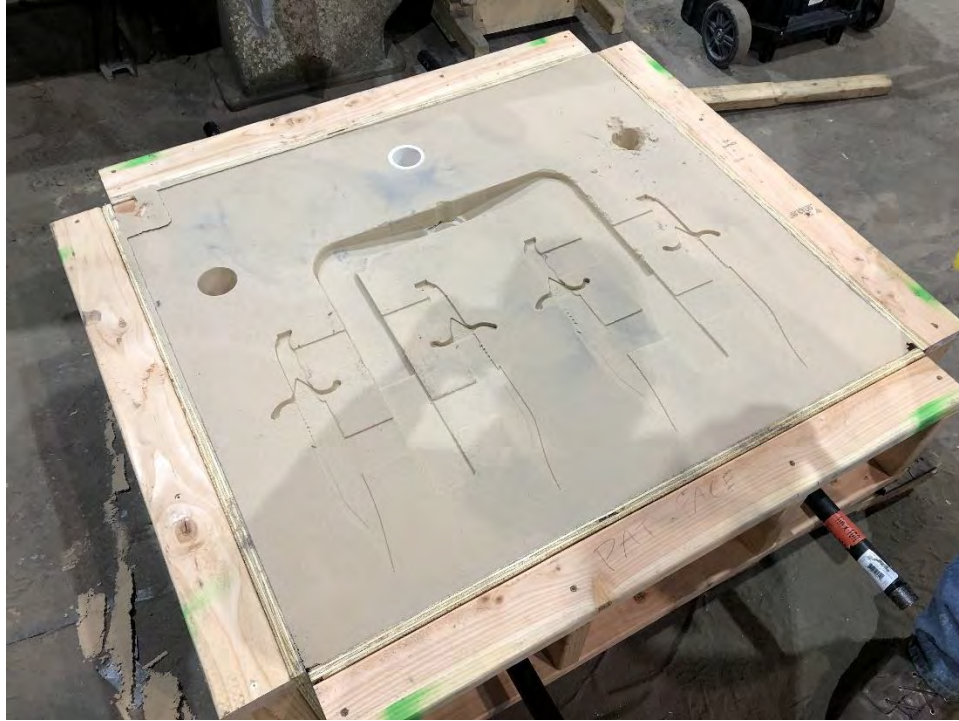


FIGURE 14: COMPLETED COPE WITH OPEN CAVITY SHOWING

FINISHING MOLDS

After the sand cured and the patterns were stripped, a alcohol based mold wash was painted onto the interior surfaces of the mold. With this final finishing process, the molds were aligned using sand cores, and the molds were ready for casting.

To be able to efficiently dose the right amount of metal in each pour, four pour basins were made out of sand and affixed to the top of the mold. This also helped the production folks hit the small molds with an open ladle and not worry about the nozzle overfeeding what the gating could handle. In an operation, this would be an extreme waste of metal and produced a very pour yield, but was necessary with the conditions for this pour.

CASTING PROCESS

The team prepared 4 separate molds with 4 Bowie Knives cavities in each mold for a total of 16 chances to get a good cast.



FIGURE 15: MOLTEN METAL DURING POUR FOR BOWIE KNIFE CASTING



FIGURE 16: ANOTHER VIEW OF POUR FROM BOWIE KNIFE CASTING

During the pour one mold suffered a significant issue in which the cope and drag separated from each other, producing a 0.325-inch-thick flashing along the parting line. Some photos of the actual castings can be seen below.



FIGURE 17: FOUR MOLDS USED IN CASTING POUR

In the image below the cope and drag separation can be seen, with liquid steel seeped out along the parting line. A bonding agent was not used in the mold that blew out. The ferrostatic pressure of the the liquid metal is an incredible force and overcame the weight of gravity acting on the cope. Using a foundry adhesive like the other molds or a clamping mechanism might have aided in reducing the parting line runout. A foundry adhesive was used on the other three and they suffered no issues.



FIGURE 18: SEPARATION FAILURE OF COPE AND DRAG

Some images of knives post casting can be seen below

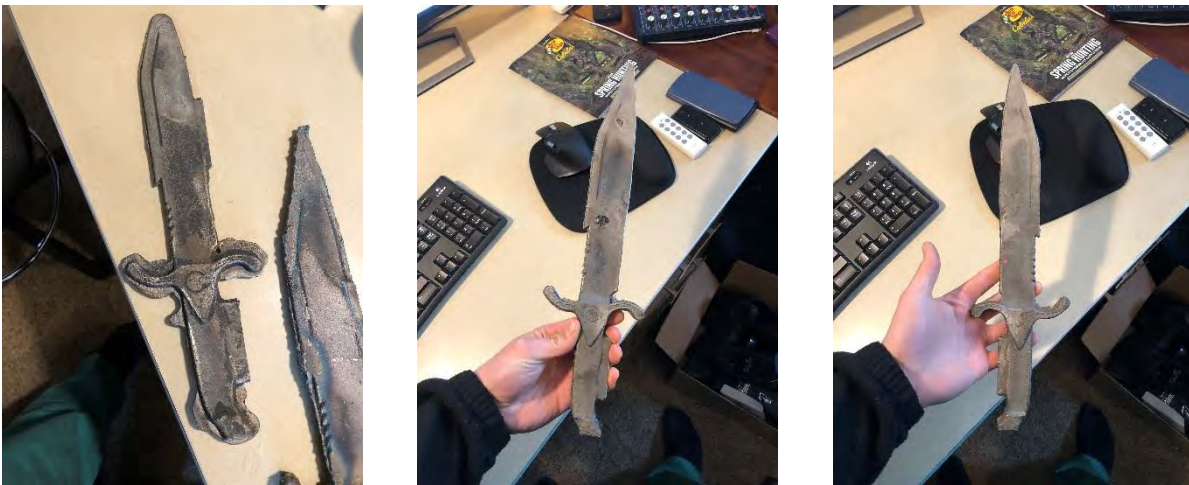


FIGURE 19: BOWIE KNIFE CASTING RESULTS

Some details did not cast well onto the knives. This included logos for UPJ and McConway and Torley as well as finer pattern details on the guard. Some additional defects present on the some

of the knives included not filling the cavity entirely and various amounts of flash that need to be removed in post processing.

CASTING RESULTS

HEAT TREAT

After pouring and shaking out the castings some burning and light grinding was required. Normalizing the castings would use a standard heating cycle and then let the knives cool with air. Most of the pieces has small imperfections due to pouring at colder temperature than desired. Some of these sections might have been repaired with light welding or other localized additive process with the steel. Following the normalizing cycle, another cycle could have been used to austenitize and quench, but looking to use a carburization process, this seemed impractical.

CARBURIZATION

The plan for the carburization process was to carburize the very edge of the blade up to a carbon content level of .80%, up from the base carbon level of approx. .25%. The very edge of the blade would be carburized only a small penetration depth into the steel, leaving the tougher lower carbon steel unaffected. As noted previously, this design intent is that only the cutting edge will be hardened to exhibit superior edge resilience characteristics, while leaving the rest of the blade softer so that it will retain its toughness and not break or crack during use. Once the carburization process is completed, the blade will be honed with its final sharpening.

CONCLUSION

At the current point in time the UPJ team has completed approx. 80% of the tasks required to cast and postprocess a functional Bowie Knife. Completed work included the entirety of the knife design, material selection, mold design, and initial casting.

Due to schedule changes brought on by the COVID-19 coronavirus some process steps had to be put on hold; tasks still outstanding include post processing the blade with heat treatments, machining, carburization, and quality evaluation of the knife. Specifically, for the quality evaluation, a combination of nondestructive dye penetrant testing and destructive hardness and impact testing was planned to ensure a quality finished product.

REFLECTIONS

Some Lessons Learned throughout the process so far include designing proper gates to feed into small thin parts, proper techniques to adhere patterns to fixed plates to prevent movement during sand compaction, and proper attachment of the cope and drag to keep them together during casting. Perhaps something as simple as a ratchet strap tightened around to lifting pipes would have corrected the flashing issue. Additionally, if the team were to cast another iteration of a Bowie Knife design some changes would be made to the part design. Since small details didn't cast well in the first cast, the designs on the knife would be simplified to allow for better casting. Also, the narrow pointed blade tip would be modified to mitigate concerns of material not filling all the way into the knife cavity.

Some observations made on the project as a whole were cemented through the alterations due to COVID-19. One such observation was complications due to lack of accessibility and time management. It was noticeably difficult to work on certain parts of the project as an entire group,

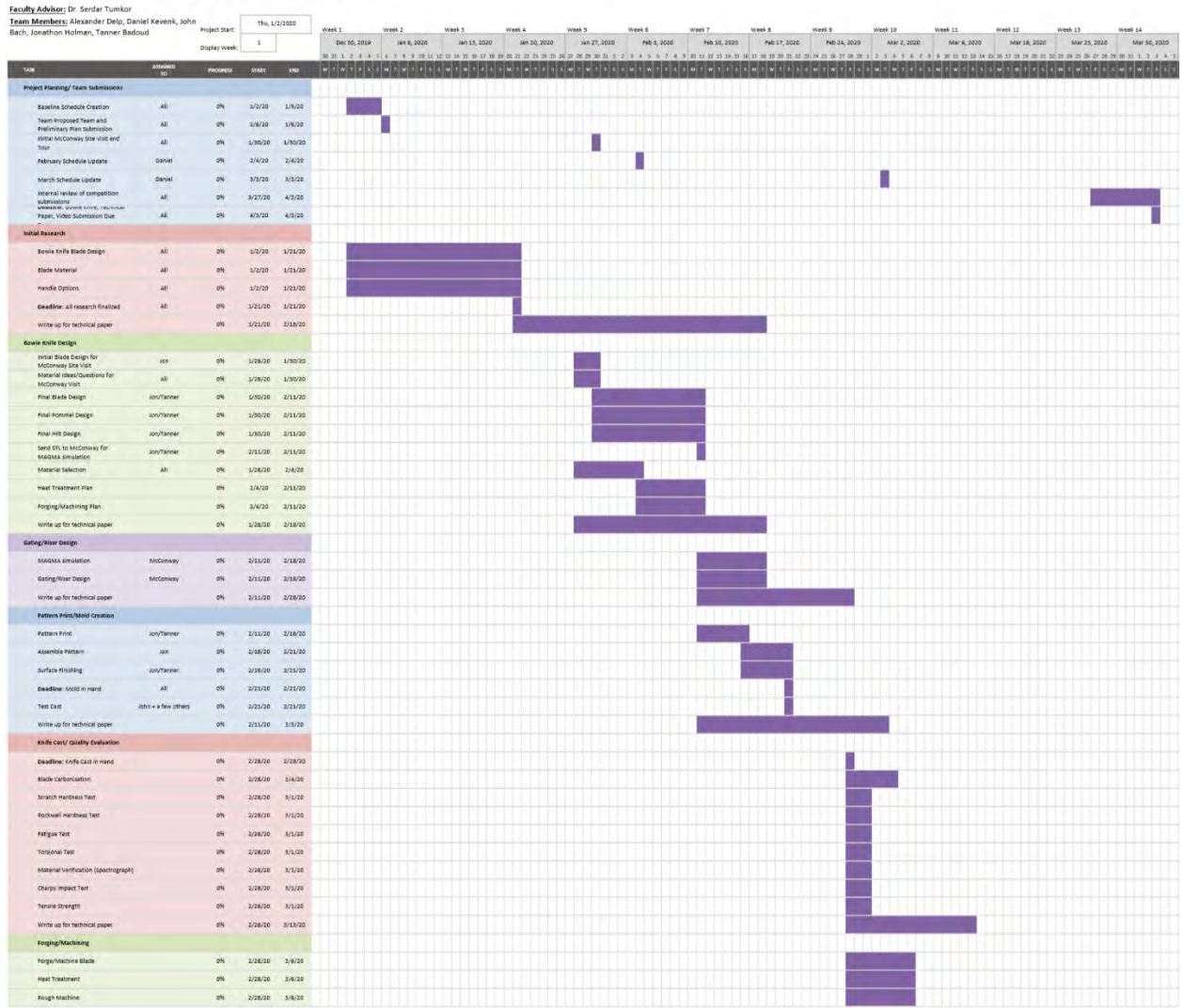
so many small pieces were delegated to individuals. This separation was only worsened by the lack of connection once students left campus.

Steps were taken to mitigate this with the use of video conferencing, but scheduling issues still often stood in the way of the team meeting as a group. In the future, these issues will be invaluable for further organization and time management, whether the team is whole or not.

APPENDIX

Full Team project schedule Gantt Chart:

PITT-JOHNSTOWN Cast in Steel Competition Project Schedule



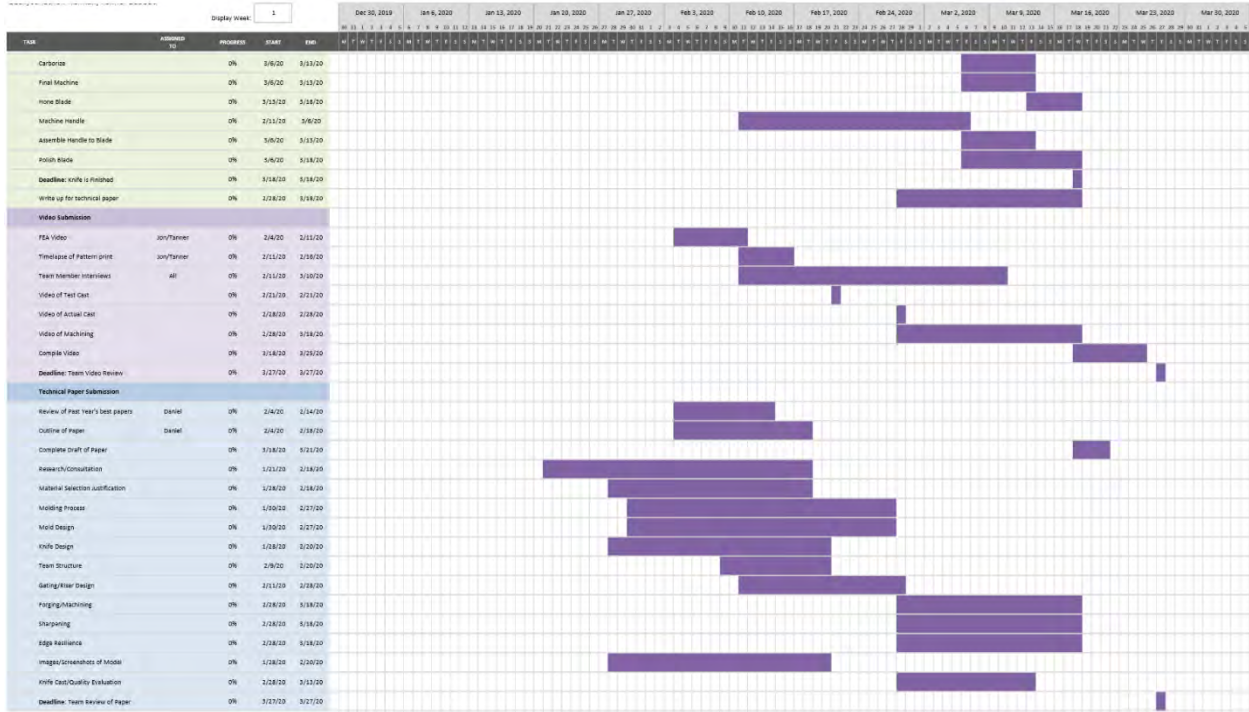


FIGURE 20: COMPLETE PROJECT SCHEDULE GANTT CHART

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