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Customizable Armor Set

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CUSTOMIZABLE ARMOR SET

By

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Abstract

This project is intended to help people who make costume armor by reducing the amount of time and money it takes to create a set of armor. Making armor can take a lot of resources for beginners, and this project is intended to help hobbyists with that process. This customizable armor set goes through the engineering design process, from the initial design of the parts to creating the prototype using vacuum forming. The prototype armor can be painted and adhered to using acrylic paint and contact cement, respectively, and fits three sizes of small, medium, and large.

Acknowledgements

I would like to thank my advisor, Dr. Christopher Daniels – University of Akron Professor, along with my report readers Jason Miller – FastForming Engineer, and Kim de Groh – NASA Senior Materials Research Engineer. I would also like to thank FastForming for sponsoring this project, allowing me to learn more about the thermoforming and vacuum forming process. I would also like to thank the employees of FastForming who helped me throughout the entire project.

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1. Introduction

This project was performed to provide a suitable armor base to build off of for people such as hobbyists, cosplayers, LARPers (live action role play), etc. As a cosplayer myself, I have found that creating armor, especially for those with little experience in the area, can be quite intimidating. It can be very time consuming as well as expensive with the material prices quickly adding up. To help this, I set out to design a product that would reduce the amount of time and money used in creating costume armor. To do this, I needed to design and create a model piece of armor that can be painted, adhered to, and fit multiple sizes. The modeling was done in Solidworks while all the machining programming was done in SolidCAM. I used my mechanical engineering experience, my work experience, and the experience of the engineers working at FastForming to create an armor base that can customized. This report goes through the engineering design process, from designing the part to creating a prototype.

1.1 Project Definition

Figure 1 provides a sketch featuring the parts of armor made in this project. The breastplate is the main piece that covers the front of the chest, while the plackart covers the lower part of the chest. The back piece is the armor piece that covers the back and is connected to the breastplate and plackart. Lastly, the pauldrons are the pieces of armor that cover the shoulders.

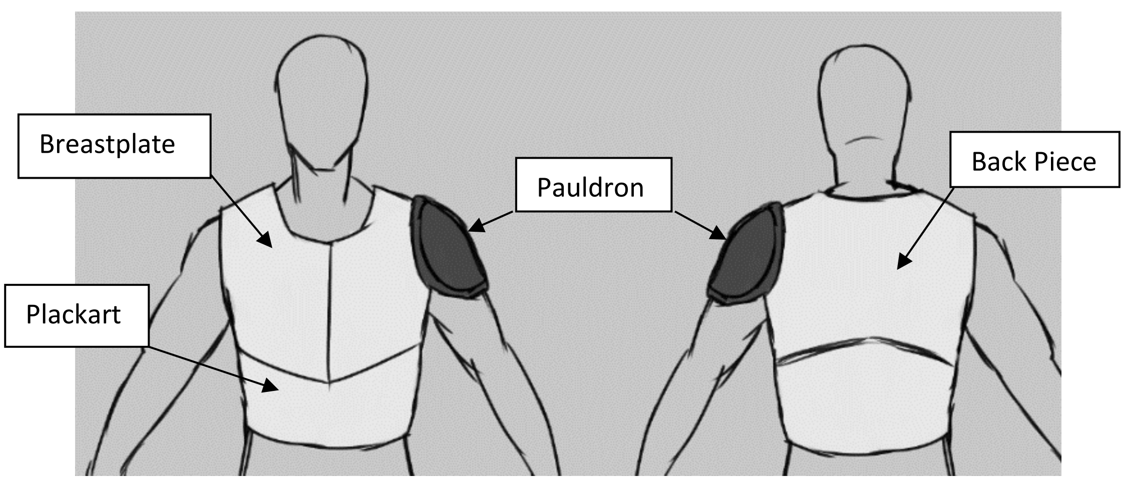


Figure 1: Armor Definitions

2. Design

2.1 Objectives

As stated in the introduction, the main goal of this project is to create a base set of armor that will allow hobbyists to make costume armor quickly and inexpensively. For this to be used by the community, there needs to be a basic set of standards that can be met. The first is to be customizable, meaning the set must be able to be glued to in some manner, as well as paintable. Glue, in this context, means adhesive. The most common and recommended adhesive in the community today is contact cement, therefore, that will be the standard. Paint can come in a variety of types, though the most common is acrylic because it is inexpensive. This will be another base level of customizability, though depending on the base material other paints can be used, but these will not be included in the standard. Another objective would be that different people can use this armor set, meaning that different sizes are required. The selection of sizes is discussed in the design approach. The last objective is that the armor needs to be attractive, due to hobbyists trying to make visually appealing costumes.

2.2 Design Approach

To properly approach this project, a short survey was distributed to people who are interested in costume armor in order to get a general idea of what the public would like to see in the product. This survey can be found in Appendix A: Survey of Consumers. Because this project is only concerned with those who have interest in the product, those who selected the “No” option for hypothetically purchasing this project are not considered. According to the survey, the most desired materials would be EVA foam, or ethylene vinyl acetate foam, and ABS plastic, or acrylonitrile butadiene styrene. EVA foam is commonly used in the costume community due to it being relatively inexpensive as well as the ability to be molded using tools such as heat guns and hair driers, products that can be easily accessible by the public. ABS on the other hand, is not a common material found in the community, due to its higher forming temperature. However, because I am working with FastForming, a vacuum and thermoforming company, both materials can be used. As long as the material is a thermoplastic, which both EVA and ABS are, it can be formed using the processes at FastForming. Because FastForming specializes in harder thermoplastics and not foams, it was decided to use ABS due to it being less expensive than other thermoplastics and more easily accessible by the company than EVA foam.

The first step to designing the amor was to decide what was vital to the project. In order to do this, an objective tree was used, which is pictured in the Figure 2 below. The weighted values were decided based on what hobbyists would find most important in an armor set.

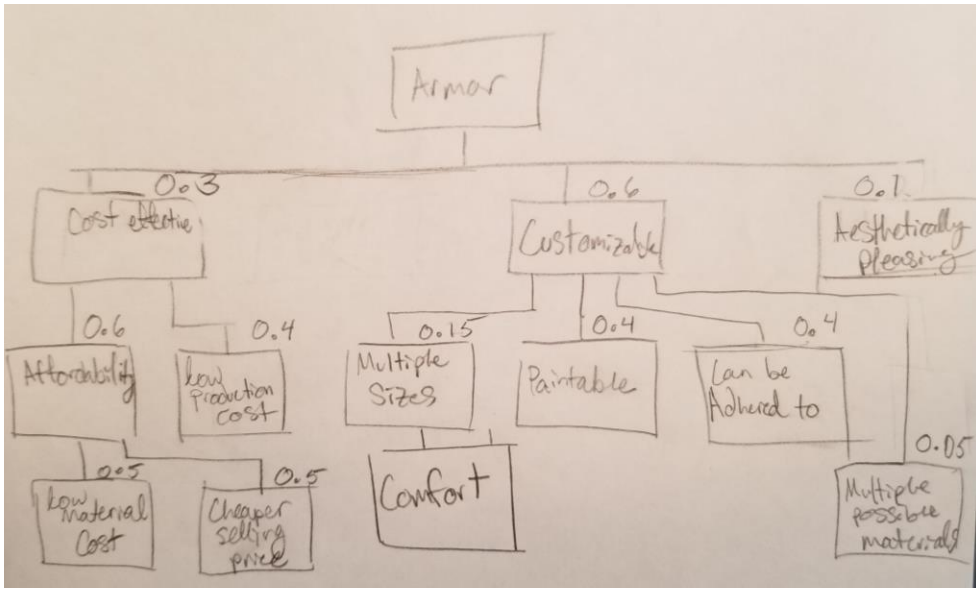
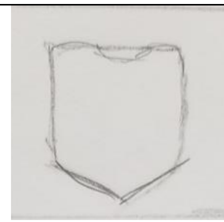
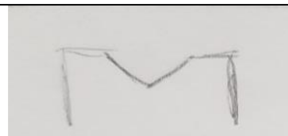
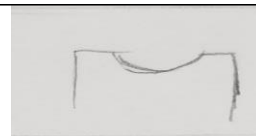
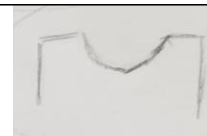
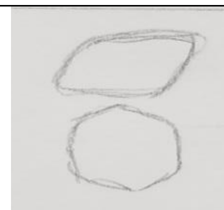
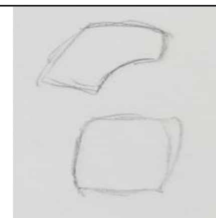


Figure 2: Objective Tree

The objective tree shows where the main focuses of the project should be as well as how the importance of these features weigh overall in said project. The most important feature is the customizability, followed by cost effectiveness, and lastly by the aesthetic aspects of the armor. This is due to the nature of the project itself. One of the great things about costumes is how diverse they can be. If this base used to make costumes cannot be made to match that diversity, then no one would desire to use this product and make the project unsuccessful. Cost also needs to be kept in mind throughout the entire project, for if the product is too expensive then it would no longer be beneficial to the costuming community.

The next step was to decide what pieces of the armor would be created with this project. Due to time constraints, only the breastplate, plackart, the back piece, and pauldrons were made, as shown in Figure 1. For costume armor, the breastplate and plackart are usually combined into one piece, therefore, they are combined in this design. Using a morphological chart shown in table 1, the different typical cuts of the armor are compared. The highlighted portions are the chosen designs for this project.

Table 1: Morphological Chart

Front Cut (Plackart)	 Flat bottom	 Pointed	 Rounded
Neck Cut (Breastplate)	 V cut	 U cut	 Rounded V cut
Pauldron Style	 Shell	 Box	 Arc

The styles chosen were based off comfort as well as aesthetic. Sharp edges in armor, such as around the neck, can be uncomfortable, therefore, a rounded V cut allows room to move but still gives a defined appearance. The rounded bottom edge prevents the armor from digging into the abdomen of the wearer and allows for a better range of movement. This also allows the person using the armor to have more surface area to customize their armor. If a flat bottom were chosen, the armor would have had to been cut higher than a rounded bottom due to mobility.

In order to be able to create a prototype later on, a standard sizing chart is required. The most logical chart to use was a costume retailer sizing chart [3], as shown in Figure 3.

Size	S	M	L	XL
Bust	33-36/84-92	37-40/94-102	40.5-44/104-112	44.5-48/114-122
Waist	28-30/72-77	32-34/82-87	36-38/92-97	40-42/102-107
Hips	34-36/84-92	37-40/94-102	40.5-44/104-112	44.5-48/114-122
Height	5'5"-5'7"/165-170	5'7"-5'9"/170-175	5'9"-5'11"/175-180	5'11"-6'1"/180-185

Figure 3: Sizing Chart

The first set of numbers in each column is the respective measurement in inches while the second set of numbers is the respective measurement in centimeters. To properly get said measurements from a person, a tape measure should be used by a second party. Measuring oneself can result in errors which can lead to incorrect sizing due to the tape measure slipping and falling out of place. The following is how to properly measure the bust, waist, and hips, respectively.

- Wrap measuring tape around the torso under the armpit over the fullest part of the chest and shoulder blades.
- Wrap measuring tape approximately one inch above the belly button, at narrowest section of waist.
- Wrap measuring tape across the hip bones, at widest portion of the body.

For the purposes of time, only three sizes from this chart were chosen for the project: small, medium, and large. This was decided because the survey taken states that the most common size selected was a medium, followed by large and extra-large. To be able to cover the range of the medium properly, it was decided to make the sizes of small, medium, and large.

2.3 Initial Design Sketches

Based off the morphological chart, an initial sketch of the armor was created and pictured below.

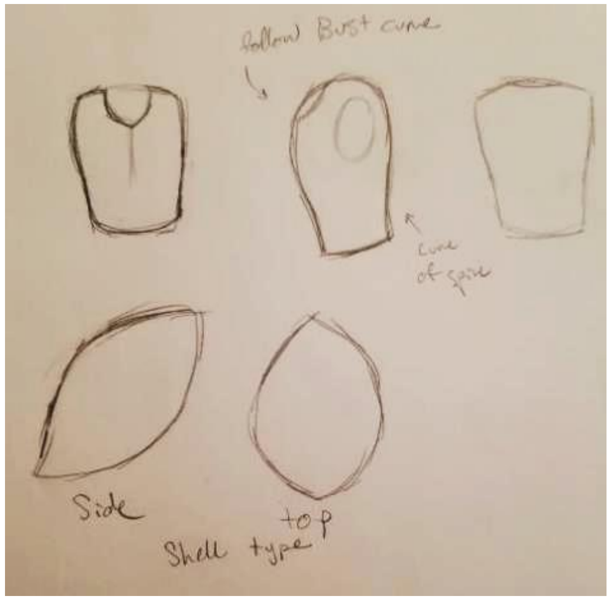


Figure 4: Initial Sketch

Because this is to be a stiff piece of armor, the sizes provided in Figure 3 will not be enough to design the piece. The irregular shape of the human torso cannot be approximated by any geometric shape, such as a cylinder, in this case. To properly capture the shape, the depth and length of the torso are necessary. This information was gathered using Reference [2], personal collection, and overall experience from sewing and costuming.

2.4 Initial Modeling

Because of the curvature of the wanted product, it was decided to use surface modeling in SolidWorks for the initial designs. 3-D models of the design were created using a number of series of splines, offsets, lofts, 3-D sketches, and filled surfaces.

3. Initial Design

Images of the initial 3-D model can be seen here.

Figure 5: Initial 3-D Model Front View

Figure 6: Initial 3-D Model Side View

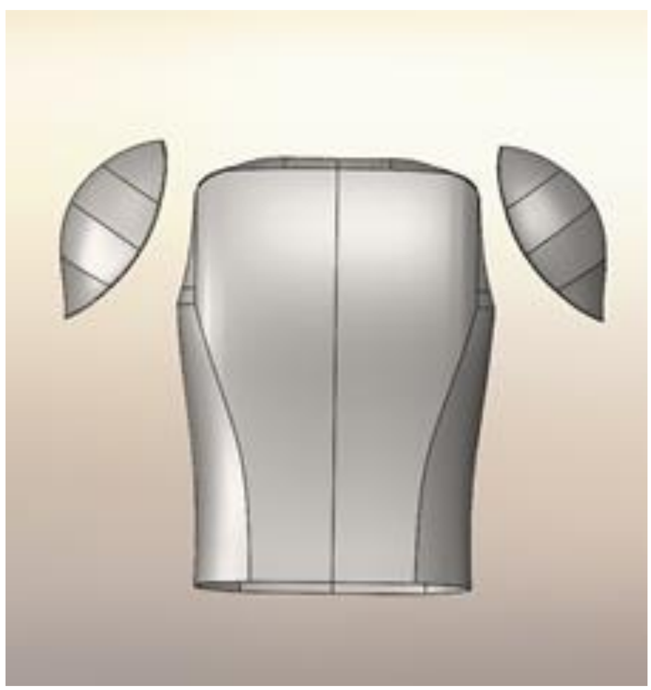


Figure 7: Initial 3-D Model Back View

4. Manufacturing Process

In order to be able to create the parts using thermoforming and vacuum forming, tooling is required. The tooling used to create prototypes at FastForming are created using Renshape, a high-density polyurethane foam. This foam is carved using the Computer Numerical Control machines, or CNC machines, giving a high precision finish for the tooling.

4.1 Creating Tooling

To begin the tooling process, the original 3-D model of the part is taken and analyzed, finding the best way to create tooling for the finished product. In this case, it was found that splitting the torso armor into two halves and combining them into one tool would be the best method, saving time and material. The tooling for the torso armor is then made by placing the two halves on the same plane and creating an offset surface. The model is then extended downwards to create a draft for forming along with different sizes. The first iteration of the 3-D model can be seen in the figure below.

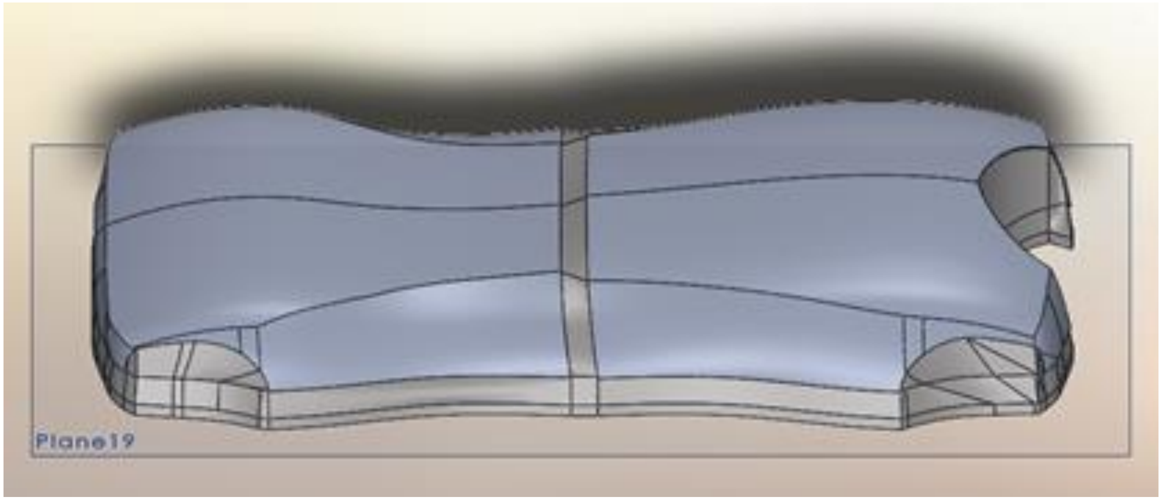


Figure 8: First Back Piece and Plackart Tooling Model

After discussing the model with FastForming engineers, it was evident that this tooling model would be difficult to form with because of the sharp edges that can be seen at the neck and arm holes. These sharp edges would prevent the part from being easily removed from the tool. It was also pointed out that with this design the neck hole could only be one size, which would not be ideal for different sizes. The tooling was then redesigned to have a more fluid continuation at the arms and neck, as seen in the next figure.

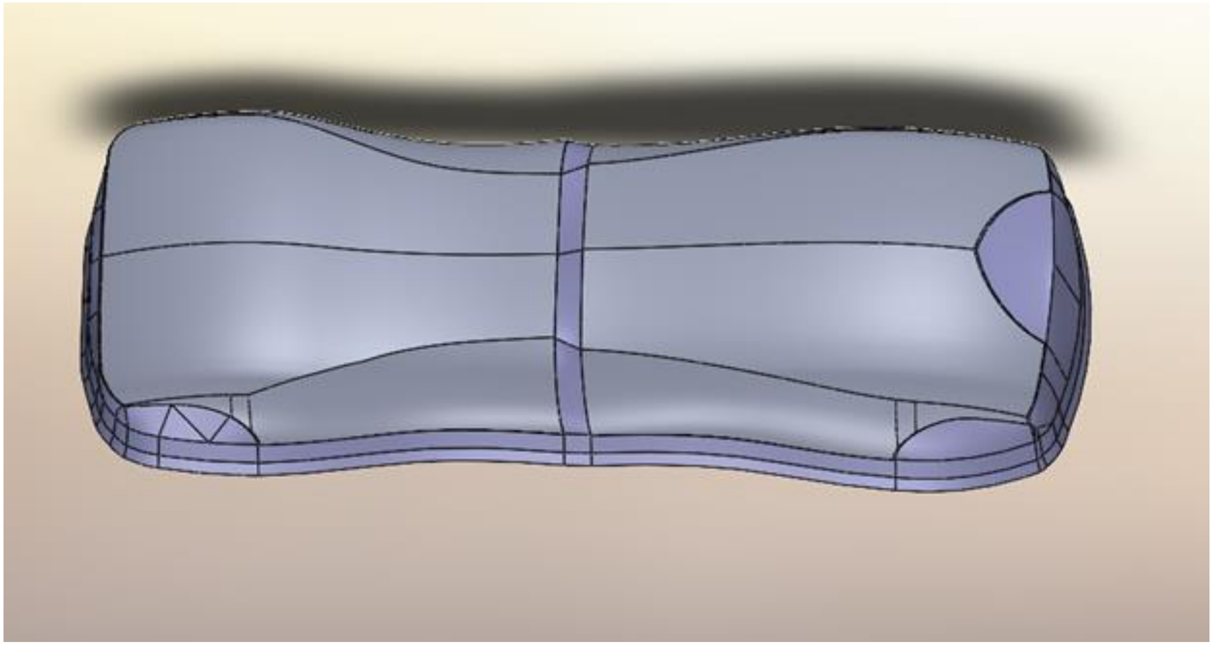


Figure 9: Final Back Piece and Plackart Tooling Model

The tool is then scaled up by a factor of 1.007 to account for shrinkage of the parts, following ISO 20457:2018(en) 294-4 and 2577, *Plastics – Injection moulding of test specimens of thermoplastic materials – Part 4: Determination of moulding shrinkage* and *Plastics – Thermosetting moulding materials – Determination of shrinkage,* respectively [4]. Though this process is not injection moulding, some standards, such as shrinkage, are applicable to this process.

The pauldron tooling model is created in a similar way to the back piece and plackart tooling, by using an offset surface. This model then extended tangentially to get different sizes, then a loft was used to create draft necessary in forming.

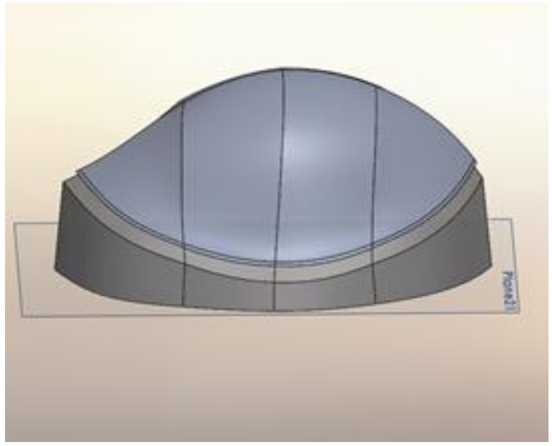


Figure 10: First Pauldron Tooling Model Side View

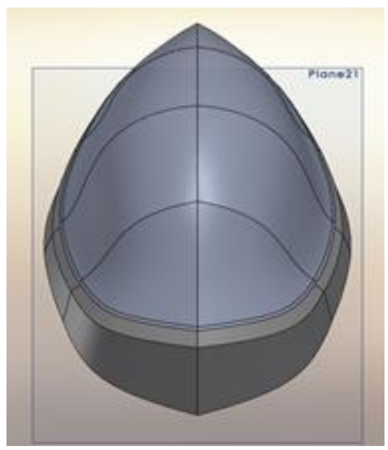


Figure 11: First Pauldron Tooling Model Front View

From these models, drawings are made following ASME Y14.5-2018, *Dimensioning and Tolerancing*, standards [1]. All measurements are in inches with a tolerance of +/- 1/8 of an inch. However, to use the CNC machine, the drawings are not used, and the programming comes directly from the 3-D model, which follows ISO 20457:2018(en) 17450-1:2011, *Geometrical product specifications (GPS) – General Concepts – Part 1: Model for geometrical specification and verification* [4]

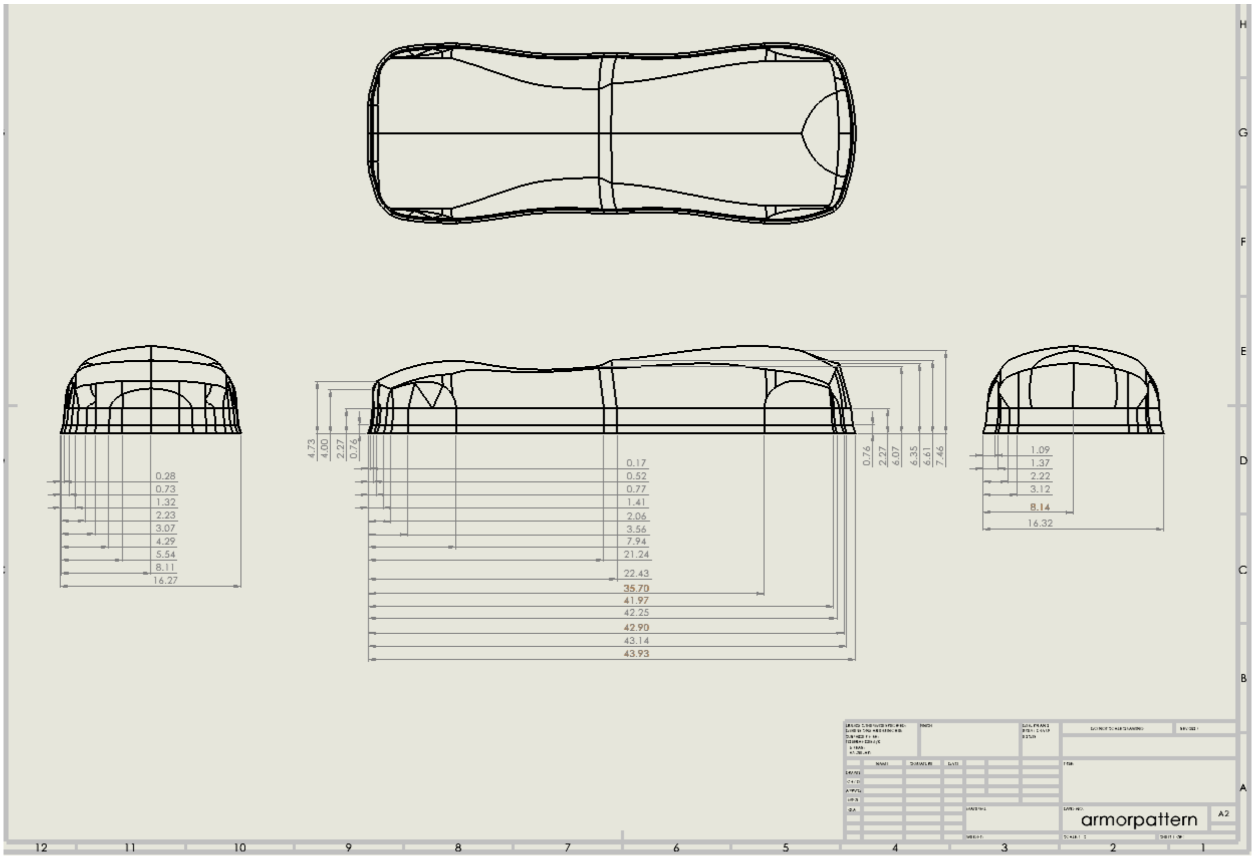


Figure 12: Back Piece and Plackart Tooling Model Engineering Drawing

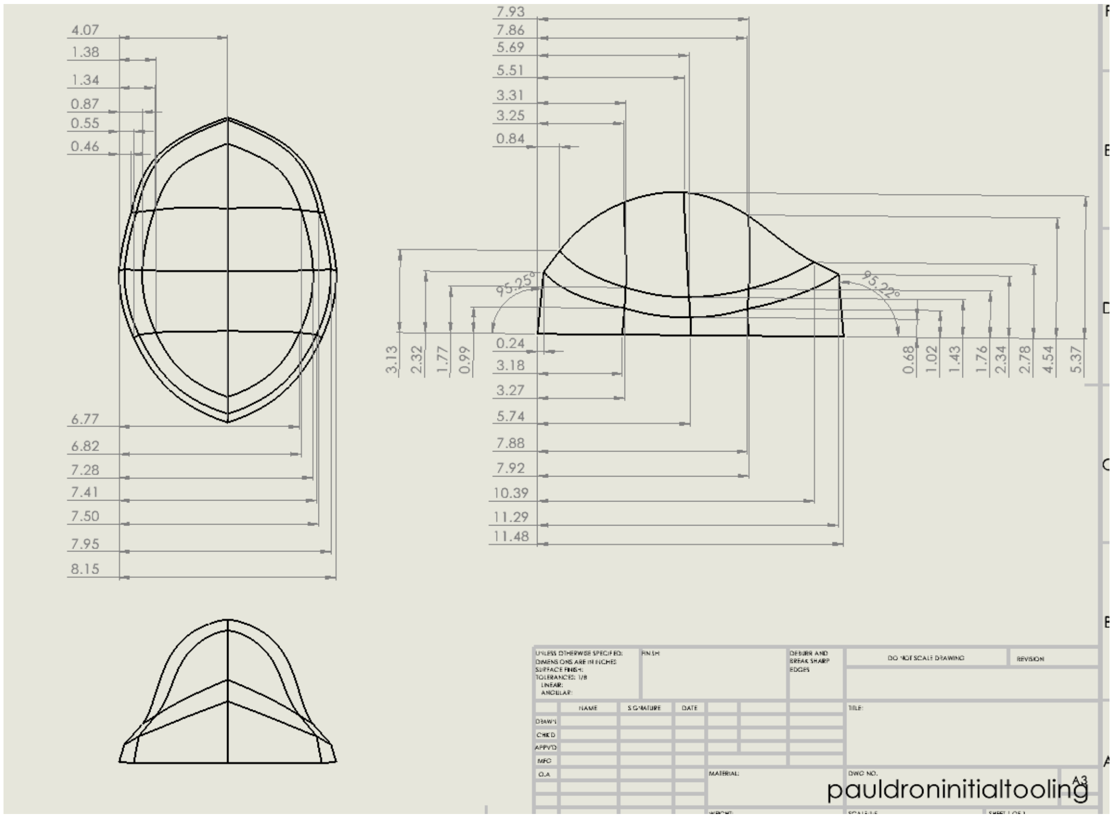


Figure 13: Initial Pauldron Tooling Model Engineering Drawing

After the models were completed, a stock model was then created. From the bottom of the tooling, a plane was inserted every one and/or two inches, depending on the tool, until the entire model has been divided. Starting from the lowest plane, a rectangle is drawn around the tooling, giving the part 0.25 inches of space on all sides, to allow for human error when gluing together the stock and cutting tolerance. The rectangle is then extruded upwards to the next plane, and this process continues until the entire tool has been covered by the stock.

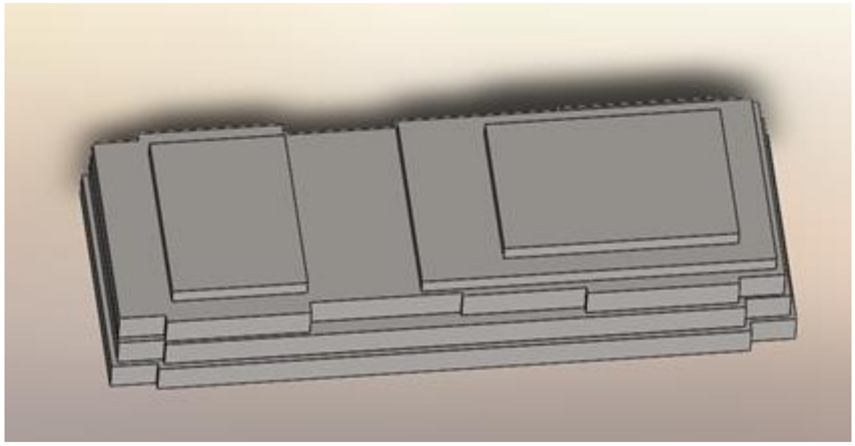


Figure 14: Stock Model of Back Piece and Plackart

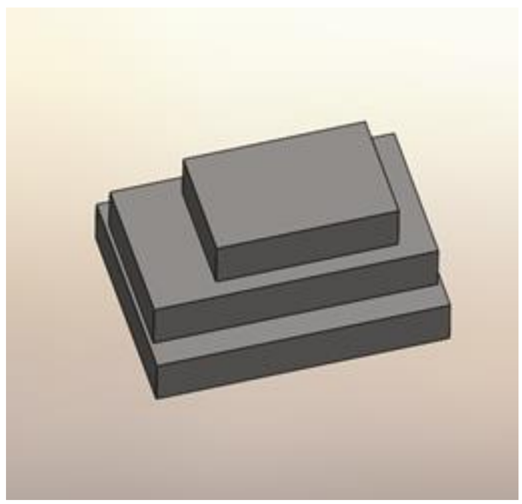


Figure 15: Stock Model of Pauldrons

The measurements from the stock model were then taken and used to cut out the stock in Renshape. These pieces were then glued in their respective places using a mixture of Bondo and resin. The mixture of Bondo and resin decrease the viscosity of the Bondo, allowing the Renshape to sit closer together overall. The finished stock pieces are then drilled to pieces of particle board to be attached to the CNC machines.

4.1.1 Finish Forming Model

Using SolidCAM, the 3-D model was converted into code to be used by the machines. After mounting the stock models, the CNC machines were then aligned with the part. Using a 0.5-inch ball nose drill bit, the tool was carved out first using a rough pass with a step size of 0.25 inches. Once the rough pass was completed, a finishing pass with a step size of 0.02 inches was implemented. In this case, the pauldron was able to be cut out in a single program, however, the back piece and plackart had to be separated into two parts. This is because of the limitations to the CNC machine itself. The machine cannot cut past a certain length without interfering with the router. To avoid this, the tool was separated into a top and bottom half. After the bottom half was cut using the procedure described prior, the top half was glued onto the part using a Bondo-resin mixture. Once the pieces were attached and the Bondo was dry, the top half of the tooling was cut using the same process. After the CNC finished cutting, the tooling was removed and then examined for any errors, such as the machine cutting in too far, voids in the Bondo, or unsmooth surfaces. All errors were fixed appropriately, whether it be filling in the voids with Bondo or finishing the surface with sandpaper. The final cut models can be seen in the figures below.

Figure 16: Unfinished Tooling for Back Piece and Plackart

Figure 17: Unfinished Tooling for Pauldron

4.1.2 Creating Vacuum Box

Particle board is used in the vacuum box making process. First, the size of the vacuum box is selected based off the tooling height and draft. The ratio of the vacuum box height to part height is approximately 1:1, but it can be reduced depending on the draft of the part. The dimensions of the vacuum box also depend on the number of parts being made. For higher quantities, a non-standard vacuum box size can be permitted because the plastic sheets will be custom ordered in said size. For smaller quantities, the vacuum box needs to fit within the standard sized plastic sheets. Once the size is selected, the tooling is connected to a piece of the particle board using Bondo, then set aside for later use. The main box component is made up of five pieces: four side pieces and a bottom. The four side pieces are attached to the bottom piece in a windmill like fashion with Bondo. Once these pieces are attached, the corners are rounded out and the entire box is then painted with a Bondo-resin mixture. The box is coated with this mixture to prevent leakage from the vacuum through the particle board. Once the vacuum box is dry, a vacuum hole is cut into the bottom of the box and the edges are sanded down to easily insert the vacuum pipe connector. Last, the tooling is glued to the top of the vacuum box and the side edges are once again sealed with a Bondo mixture. A completed vacuum box can be seen in Figure 18 below.

Figure 18: Completed Vacuum Box for Back Piece and Plackart

4.2 Forming Prototypes

Before any forming can be done, the ABS plastic needs to be dried in an oven at 165 degrees Fahrenheit for over 24 hours, though this time increases with the thickness of the plastic. This process removes the moisture from the plastic. If moisture were to remain in the plastic during the forming process, the moisture would become steam and then become voids in the plastic once it evaporates, leaving holes. If this were to happen, the plastic becomes unusable in this industry.

Because these are prototypes, the large forming machines are not used. Instead, each part is hand formed, using the backs of the forming ovens. When hand forming parts, a frame is required. The frame is made to be the same size as the plastic sheets and is made from wood. With a wooden frame, it is possible to attach the plastic to the frame with staples, a relatively inexpensive and fast process. The plastic is then cleaned off using pressurized air and then inserted into the oven. Preparation for this process can be seen in Figure 19.

Figure 19: Preparation to Form Pauldrons with Completed Vacuum Box

For ABS, the thermoforming oven temperature is set to 1200 degrees Fahrenheit. How long the plastic is in the oven differs on the part, and it was typically not measured by time, but for how much the plastic sagged. Once the plastic was deemed ready, the frame was removed from the oven and placed over the tooling and the vacuum was turned on. The frame would be held down for approximately 30 seconds and then the material was cooled down to around 150 degrees Fahrenheit. The part is then taken off the tooling and pried out of the frame. Once the part has cooled down to room temperature, it can be trimmed. Because these are prototypes, the parts are trimmed using the bandsaw instead of the five-axis CNC machine. To properly trim the parts, first the staples are cut out of the plastic and thrown away, while any other cut off excess material is put into a gaylord to be grinded and recycled. A final vacuum formed part before being properly cut out can be seen in Figure 20.

Figure 20: Final Formed Back Piece and Plackart

4.3 Redesign Pauldrons

After finishing the prototypes for the pauldrons, we discovered that they were too narrow to fit the average human shoulder comfortably. Not only were the pauldrons too narrow, but they were too tall as well, for if the part were to fit on the shoulder they would extend too far from the body. With thermoforming, there is no feasible way to change the part after it is formed, therefore the pauldrons needed to be redesigned. However, at this point, the entire forming tool was created, and to remake it would take too much time and money.

To complete the redesign quickly and efficiently, the new model was created to be contained entirely within the prior versions Renshape tooling. By doing this, not only would we be saving on the raw material, but time as well. Not only did we not have to go through the entire process of creating new stock, but we also did not have to create a new vacuum box, for we were able to mount the current vacuum box to the CNC machine and trim the Renshape from there. After the trimming was completed, all that was left was to fix up the vacuum box where it had been attached to the CNC machine and reform the parts. The prototyping process is the same as described prior.

In order to create the new model, the old prototype was examined. By warping one of the old prototypes, it was possible to see how much wider the new version had to be, along with the maximum pauldron height. It was seen that the newer model needed to be wider by 1.25 inches and the maximum height of the model was to be around 4.9 inches tall, approximately half an inch shorter than the original model. With this in mind, the same 3-D modeling process as before was followed to create the new pauldron model, which can be seen in the figures below.

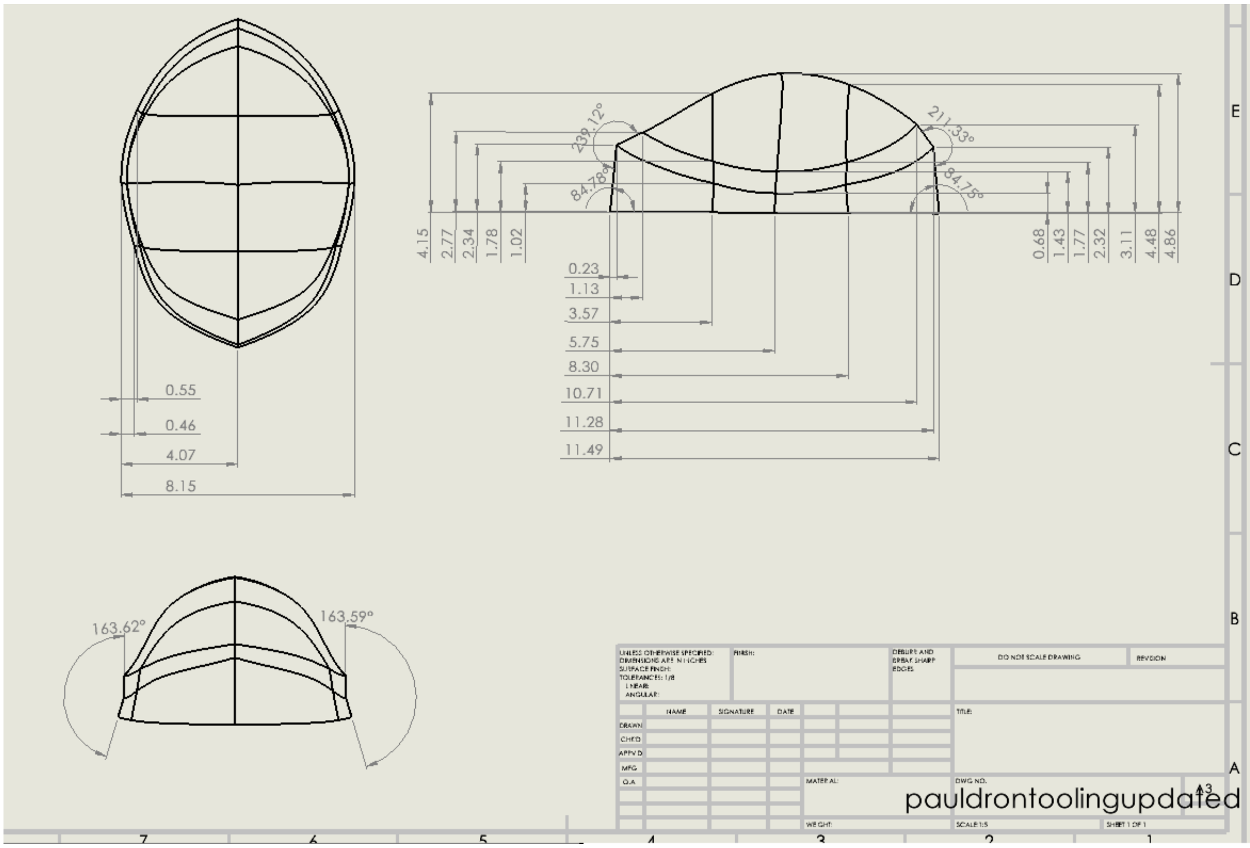


Figure 21: Pauldron Tooling Model Engineering Drawing

4.4 Production Tooling

Due to time constraints as well as finances, a final production tool was not made. The current tooling made of Renshape is good for short term use. If the Renshape is used for long periods of time, the heat will eventually cause the Renshape to expand, deforming the final product. Therefore, the final production tool is made from epoxy, which can withstand high temperatures. If this project were to continue, these would be the next steps taken.

After the prototypes are approved, the Renshape tooling is taken back into the tool room where any imperfections are fixed, and the surface is sanded with very fine sandpaper. A casting box is then created around the prototype tooling. The surface is waxed to allow an easier release for the casting and the edges are sealed with a polymer clay. The box is then sealed and filled with urethane. Once the urethane has hardened, the box is dismantled, and the casting is removed from the prototype tooling. This cast is then checked for imperfections, such as chipping. Once the cast is deemed satisfactory, the entire cast is sanded until smooth with fine sandpaper. This process continues the same as the urethane casting, however, the next cast is made of an epoxy. Urethane is not used in the final production tooling because urethane does not perform well at high temperatures. Once this process is complete, the tooling is ready for automated machinery and large-scale production.

6. Costs

Because this is a product that would theoretically be sold, calculating the cost to produce as well as the selling cost follows the same procedure as all other parts at FastForming. All dollar amounts are in USD.

First, an analysis of machine costs and labor needs to be made. The cost to run machines vary on the size. For the larger machines, such as the five-axis CNC and the large oven, each cost approximately $150 per hour. For the smaller machines, such as the three-axis CNC and the small forming oven, each cost approximately $90 per hour. The pauldrons can be created in the small forming oven, however, the back piece and plackart are too large and must be made in the large oven. The cost of labor, with taxes, is approximately $25 per hour. This information is used in later calculations.

The sunk cost of the tooling is then calculated. The Renshape used in this project costed $900, and approximately three gallons of Bondo were used, each costing approximately $40. The time taken on the CNC machines was approximately five hours on the five-axis CNC and 2 hours on the three-axis CNC, resulting in a machine cost of $930. Therefore, the total cost to create the tooling would be $1,950.

For a 3/16-inch plastic sheet that is 24x55 inches, it costs $17.45 per sheet. Assuming that no errors are made in forming the parts only one sheet of plastic is required for the back piece and plackart wile less than one sheet is required for the two pauldrons. This shall be rounded up to two sheets of plastic, meaning that the total material cost of the plastic for a set of armor would then be $34.90.

The last factor to account for is the cycle time to form the armor parts. Rounding to the nearest minute, to form one pauldron took five minutes while forming the back piece and plackart took eight minutes. This means that six sets of pauldrons can be made per hour while seven sets of back pieces and plackarts can be made per hour. Assuming that there are no errors while forming, a total of six sets of armor can be made per hour, which would cost $265 per hour to form on the small and large forming oven and accounting for labor. The material to make the six sets would then come out to be $209.40 per hour.

The cost to make the parts, without the sunk cost, the formula is as follows:

$$Armor\ Cost = Labor + Machine\ Time + Material$$

Therefore, the cost to create six sets of armor, assuming it takes one hour, would be $474.40. Dividing this by six results in each armor set costing approximately $80. However, because of the overlap in forming that was rounded down prior, the actual cost would be lower. According to FastForming, they would sell each set for approximately $70. According to the survey in Appendix B, the majority of consumers would purchase this product if it were priced between $50 and $100, meaning that the cost of the product is seen to be reasonable.

7. Final Results

All the design verification standards have been met and is elaborated on in Appendix A. ABS is capable of being adhered to and painted, while the design hits the specifications to fit small, medium, and large sizes.

One size of the final product can be seen below.

Figure 22: Final Product

According to FastForming members, along with people who responded to the survey, the armor is visually appealing, which means that the prototype meets all the objectives stated for this project.

7.1 Discussion

Overall, the product turned out well for a prototype. The pauldrons are ideal, where the back piece and plackart have room for improvement. In the final product, there are very sharp corners located around the arms and neck, which is not visually appealing. The armor should be more fluid, having a more continuous shape that matches the body. Luckily, this can be easily fixed by working on the tooling itself, sanding out the sharp corners by hand. For a more efficient and repeatable cut, the model should be trimmed by the five-axis CNC machine instead of by hand. Cutting with a CNC machine will also allow the different sizes to be easily made and reduce the amount of time trimming each part. Once these steps are completed the parts would then be ready for consumer use.

References

[1] American Society of Mechanical Engineers. (2019). *Dimensioning and tolerancing*. New York.

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a. Sizing Chart

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a. Engineering Concepts

Appendix

A Requirement and Verification Table

Measuring the prototype armor verifies that the armor is within the small, medium, and large range, though the proper sizes are achieved depending on how the prototype is cut. The sizing is also verified by testing done by employees of FastForming, trying on the armor depending on their measurements. According to the employees, the armor fits comfortably.

To verify if acrylic paint would stick to the ABS, a simple paint test was done. Two sheets of ABS were painted, starting with one layer of acrylic in the center and increasing to five layers of acrylic paint as it goes outwards, which can be seen in the figure below. The right portion of the ABS has been sanded prior with 300 grit sandpaper while the left portion was left untouched. Both the smooth and rough texture was tested as such. An equal amount of pressure with a sharp object was applied to the paint to see how it would chip. It can be seen that the sanded portion holds the paint better than the smooth portion, but still chips under pressure, which is not surprising. Therefore, while using acrylic on this product, there needs to be a protective coating.

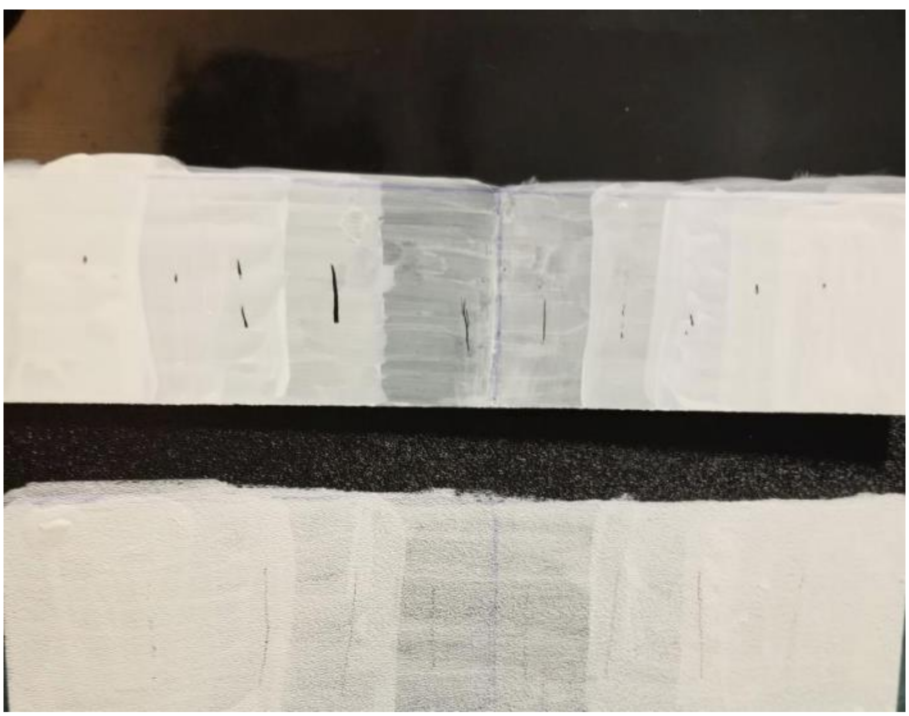

Figure 23: Acrylic Paint Test

The final test is to see whether or not contact cement would allow additions onto the armor. Taking a piece of ABS and following the instructions for contact cement, a piece of EVA foam was attached to the plastic. Because there are two possible textures, the EVA foam was attached to both. After waiting the stated time period, the results can be seen in the figures below.

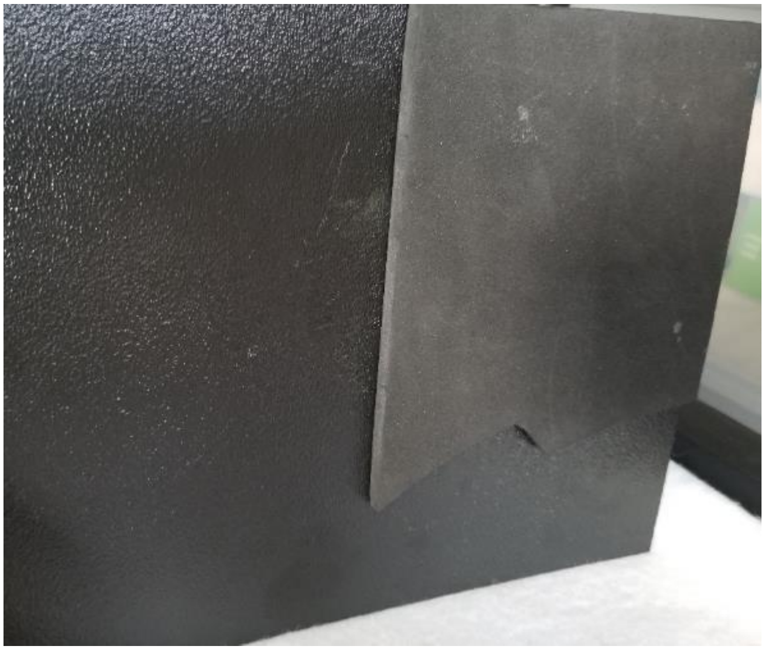

Figure 24: EVA Foam Attached to Rough Textured ABS

Figure 25: EVA Foam Attached to Smooth Textured ABS

It can be seen that the EVA foam adhered to the ABS. The plastic could be jostled around without the EVA falling off. To see how strong the connection was, it was attempted to pull the two pieces apart. It is entirely possible to separate the two pieces, but it took quite a lot of force, way more than what would be exerted while wearing the armor. Thus, the armor passes the adhesive test.

Table 2: System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Adhesive a. Contact Cement	1. Glue EVA foam to ABS	Y
2. Paint a. Acrylic Paint	a. Painting of ABS	Y
3. Sizing	2. Different Size requirements met	Y
4. Visually Appealing	3. Questioned if the appearance was appealing	Y

B Survey Results

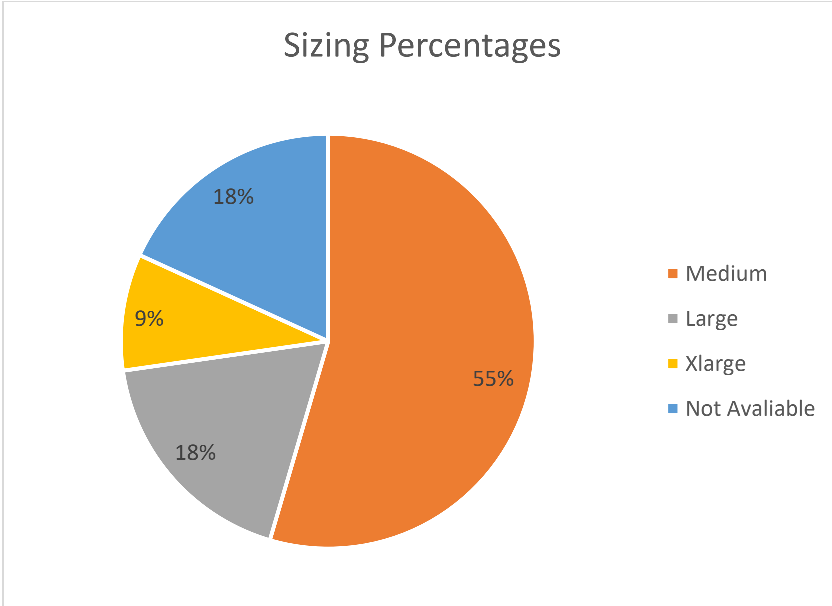

Figure 26: Survey Sizes Results

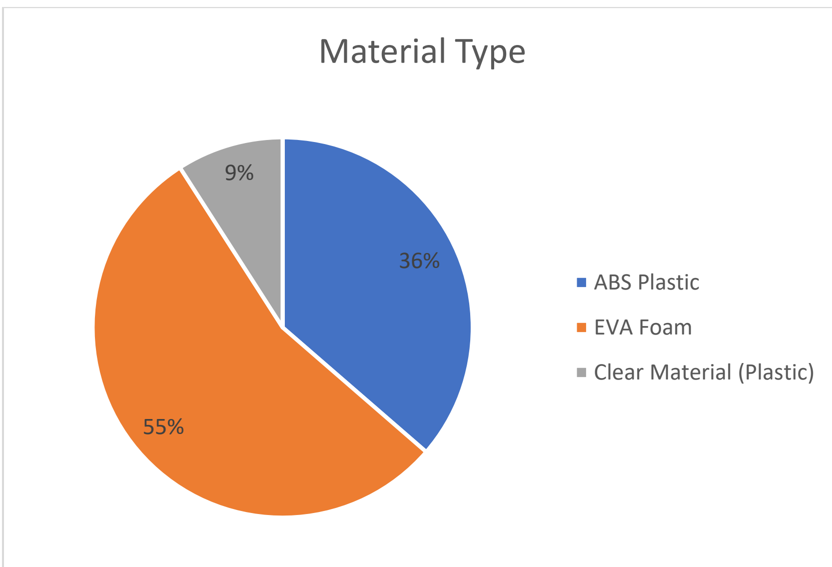

Figure 27: Survey Material Results

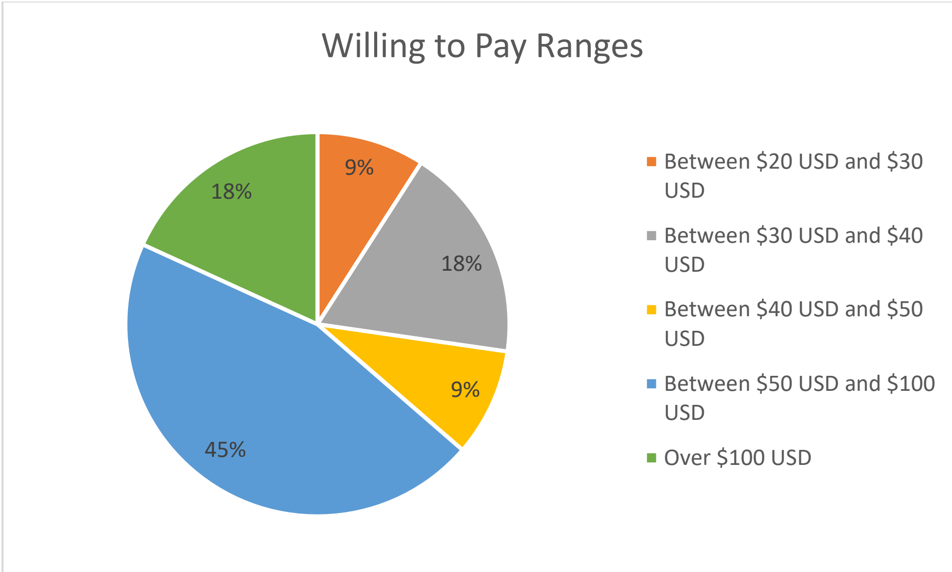

Figure 28: Survey Pricing Results

C Extra Images of the Tooling Process

Figure 29: Stock of Back Piece and Plackart

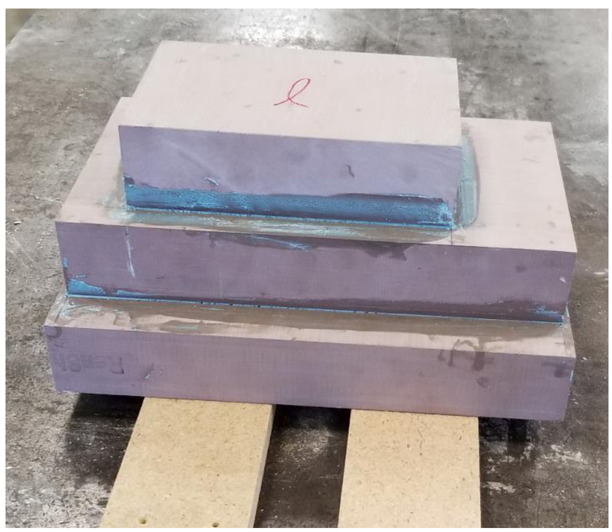

Figure 30: Stock of Pauldron

Figure 31: 5 Axis CNC Cutting Tooling

Figure 32: 3 Axis CNC Cutting Tooling

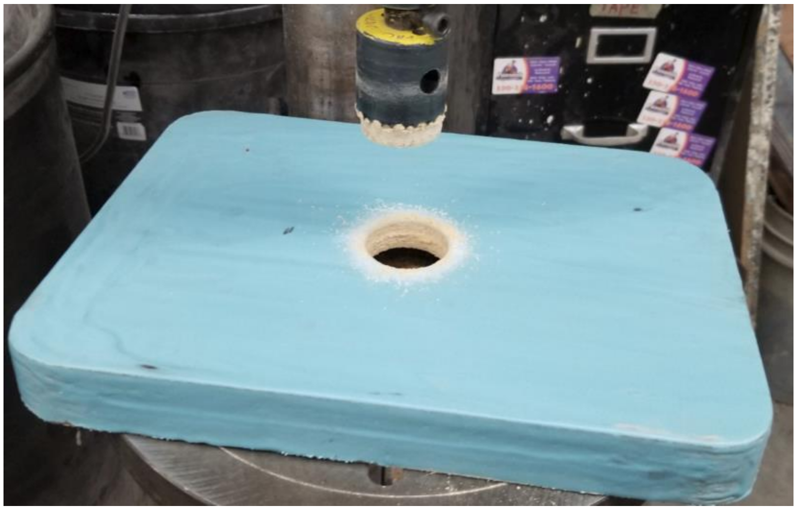

Figure 33: Drilling Hole in Vacuum Box