HYBRID THERMOPLASTIC COMPOSITE BALLISTIC HELMET FABRICATION STUDY

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ABSTRACT

Thermoplastic advanced composites are a rapidly growing field of advanced materials. Comprising reinforcing fibers embedded in a matrix of thermoplastic resin, these materials offer high specific strength and stiffness and low density. In addition, thermoplastics' high toughness makes their use appealing in applications that require energy absorption and strength after impact. Thermoplastic advanced composites also offer potential benefits of reduced cycle time and in-plant air quality for manufacture. This paper describes an initial investigation into the fabrication of a thermoplastic anti-ballistic infantry helmet. The objectives of this investigation were to assess the potential for manufacturing a high-quality helmet via thermoforming and to measure the cycle time for each processing step. The helmet construction included an inner aramid composite anti-ballistic liner and an outer carbon-fiber-reinforced thermoplastic shell. The results of this study indicate a potential for cycle time improvement using thermoplastics, but further work would be required to improve heat transfer during material pre-heating prior to forming and to automate several process steps.

KEY WORDS: Advanced Composite Materials/Structures, Hybrid Materials/Structures, Thermoforming/Thermoshaping

1. INTRODUCTION

Thermoplastic advanced composites have long held potential for mass-producing lightweight structural parts. Unlike thermoset-based composites, which undergo time-consuming chemical crosslinking during processing, thermoplastic-based composites are typically processed using only heat and pressure. Short and long chopped fiber reinforced thermoplastic composites are in widespread production using injection molding, and efforts are underway to achieve similar less-than-one-minute cycle times for higher performance, continuous fiber reinforced thermoplastic composites. In this investigation, Fiberforge's thermoforming manufacturing process was used to fabricate anti-ballistic (ballistic) helmets for evaluation by the Army Research Laboratory (ARL). This paper describes the helmet design, materials and processing methods used, cycle time measured for each step, and potential areas of cycle time improvement.

2. HELMET DESCRIPTION

The helmet shape is one that the Army has developed for its Future Force Warrior (FFW) initiative. Currently, the US Army uses helmets of a different design. These helmets, called PASGT helmets, are made using a composite comprising aramid fabric in a thermoset matrix. One overarching goal of the FFW helmet is to reduce weight compared to the PASGT helmet (1). The construction must also be strong enough to withstand the daily wear of a soldier's activities and provide improved ballistic protection. The FFW construction that Fiberforge investigated includes a tough, stiff carbon-fiber reinforced thermoplastic shell bonded to an aramid reinforced thermoplastic composite ballistic layer. The carbon fiber shell stiffens the helmet and improves wear resistance. The aramid provides ballistic performance.

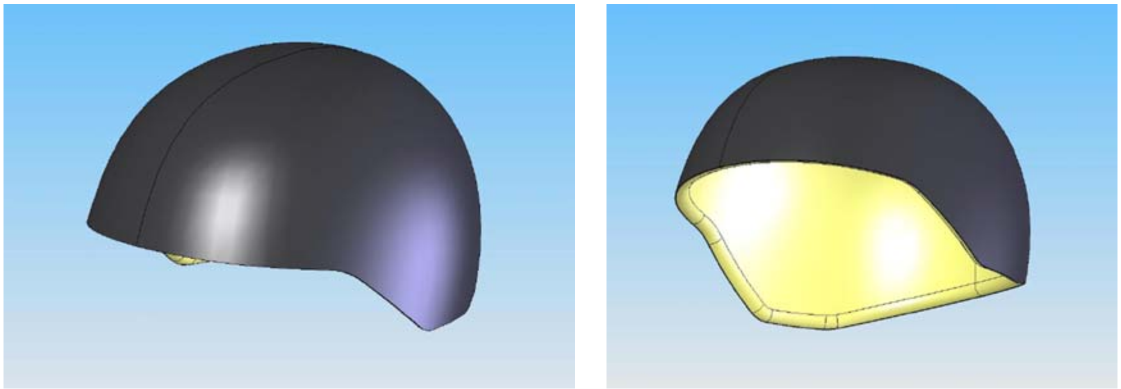


Figure 1. Hybrid FFW helmet design

To meet the Army's weight target, the helmet's areal weight must be 8,540 g/m^2 (1.75 lb/ft^2, or psf), including both the structural and ballistic layers (2). This areal weight and the desired ballistic performance of the helmet drove the design of the helmet. The desired ballistic performance requires an areal weight of 7,320–7,810 g/m^2 (1.5-1.6 psf) of aramid composite. This amounts to 38–40 plies of material at 195 g/m^2 per ply (0.040 psf/ply).

3. FIBERFORGE MANUFACTURING PROCESS

The Fiberforge manufacturing process includes four steps: automated lay-up, consolidation, thermoforming, and trimming (3). In the automated lay-up step, Fiberforge's Relay™ station is used (Figure 2). This automated machine rapidly lays up strips of unidirectional thermoplastic prepreg tape into a flat, net-shape blank. Parts made with this machine can have any laminate orientations, ply build-ups, holes, etc., which allows for preforms to be optimized for each part (4). This machine was used to fabricate the carbon fiber shell blanks for the helmet. However, the aramid used in the helmet was provided as a roll of woven fabric, and therefore was cut to shape by hand.

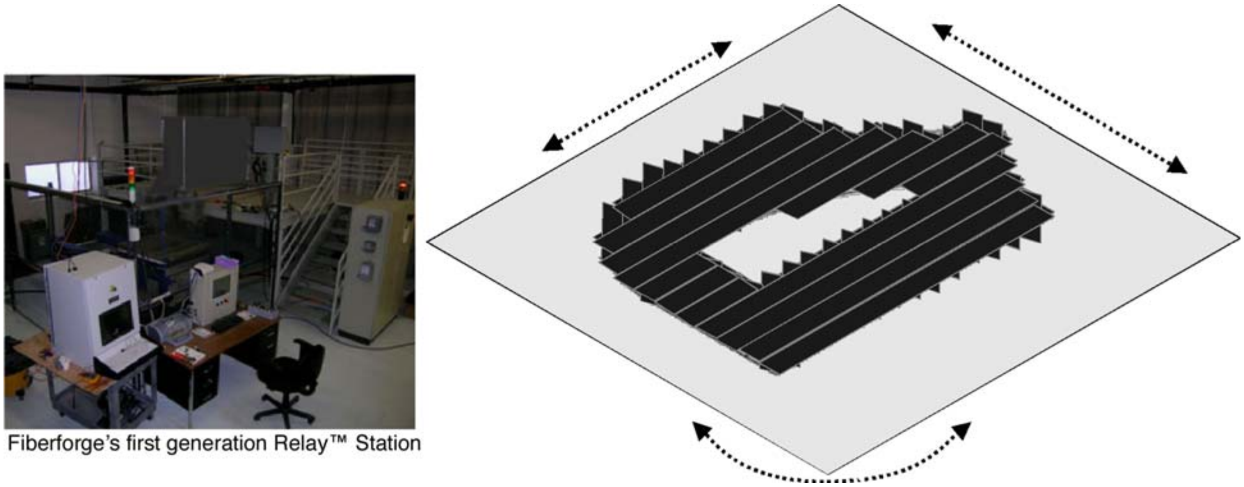

Fiberforge's first generation Relay™ Station

Figure 2. Structural shell blank manufacturing cell, with a generic tailored blank illustrated

Following layup, Fiberforge typically consolidates the tailored blank to fuse all of the plies together. In this investigation, the carbon-fiber blank was consolidated, but the aramid plies were not. Instead, the ballistic plies were loosely stacked and consolidated during the thermoforming operation.

The helmet shells were formed using a 408 tonne (900,000 lb) thermoforming press. Figure 3 illustrates the steps of the process as it was performed for the helmet fabrication.

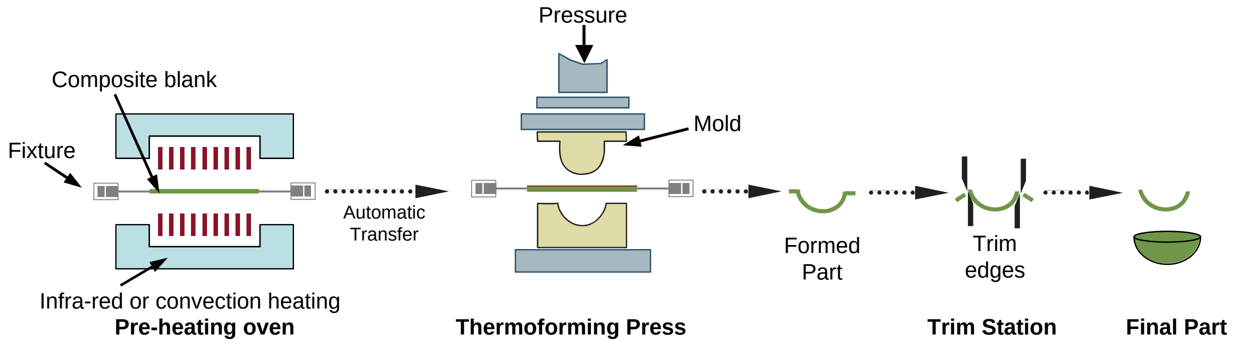


Figure 3. Thermoforming process steps

The carbon fiber blank and the aramid plies were stacked and fixtured in a shuttle frame. Springs were used in the fixturing to provide membrane tension on the blank to help control ply movement during forming.

Fiberforge hand trimmed the helmets to their final shape. Aramid's toughness makes it difficult to cut using traditional steel or carbide tools. Therefore, the helmets were trimmed with water-cooled diamond-coated cutting tools.

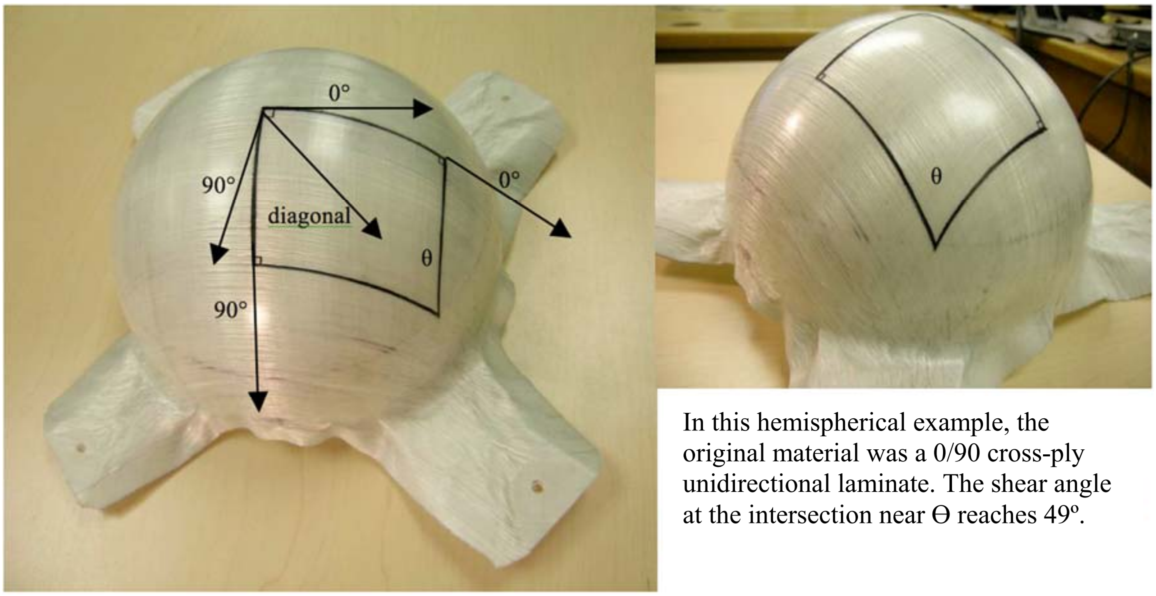
4. **MATERIALS DESCRIPTION**

***4.1* Carbon Fiber/Polyphenylene Sulfide Structural Shell** The starting material for the structural shell was AS4/polyphenylene sulfide (PPS) prepreg tape. PPS was chosen because of its high stiffness, toughness, environmental resistance, low moisture absorption, and wide service temperature range. Given the relatively low weight budget available for the carbon fiber shell and its purpose of improving helmet stiffness, matrix modulus was a key factor in the resin choice. With a tensile modulus of 3,600 MPa, PPS has more than twice the modulus of two alternative resin systems, polypropylene and polyamide 6.

Property	**Value**
Density (g/cm^3)	1.4
Moisture absorption, equilibrium (%)	0.02
Tensile modulus (MPa)	3,600
Tensile strength (MPa)	86
Notched Izod Impact (J/cm)	0.3

Table 1. Properties of polyphenylene sulfide (5)

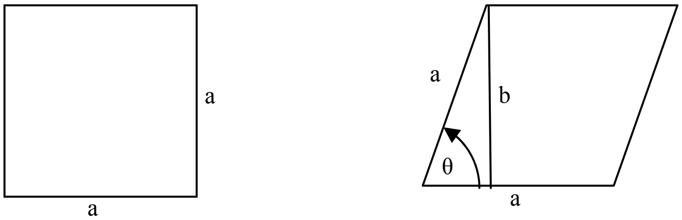
4.2 Aramid/Thermoplastic Polyurethane Anti-Ballistic Layer The ballistic helmet shell was formed using sheets of Dupont Kevlar 49. This material comprises a biaxial weave of aramid with a film of proprietary thermoplastic polyurethane laminated to one side. To achieve the target ballistic performance, 39 plies are required. At 0.23 mm (0.0091 in) nominal thickness per ply, the total thickness of the ballistic layer of the helmet is 9.01 mm (0.355 in). Thermoforming such a thick section into the compound-curved helmet shape can result in significant wrinkling and folding of the material, which results in non-uniform thickness of ballistic material in the finished part. This phenomenon has been researched extensively with woven fabrics (6). When a tensioned cross-ply material is formed into a complex curve, the angle between the warp and weft fibers (i.e., the shear angle) changes, as demonstrated in Figure 4. Since the elongation of aramid is low (2.4 % (5)), this change in shear angle is the main mechanism by which the fabric conforms to the mold geometry. At the crown of the helmet, the shear angle is 90°. Progressing down from the crown along the direction of the warp and weft fibers, the shear angle remains approximately 90°, while along the diagonal, the shear angle changes considerably.



In this hemispherical example, the original material was a 0/90 cross-ply unidirectional laminate. The shear angle at the intersection near Θ reaches 49º.

Figure 4. Trellising (7) illustrated

As the shear angle decreases from 90°, the part locally thickens. This thickening behavior can be approximated by calculating how a unit area of a piece of composite changes as its shear angle (θ) decreases from 90°.



$A_{start} = a^2$ $A_{end} = ab = a^2 \cdot sin\theta$

Figure 5. Thickening due to shear angle changes

If the original area (A_{start}) of the composite is a^2, where a is the length of each side, then the following equations describe the relationship between the starting laminate thickness (t_{start}) and the ending laminate thickness (t_{end}). This relationship is also illustrated in Figure 6. V represents the volume a unit of material.

$$A_{start} = a^2 \quad [1]$$

$$V_{start} = a^2 \cdot t_{start} \quad [2]$$

$$A_{end} = a^2 \cdot sin\theta \quad [3]$$

$$V_{end} = a^2 \cdot sin\theta t_{end} \quad [4]$$

$$V_{start} = V_{end} \quad [5]$$

$$a^2 \cdot t_{start} = a^2 \cdot \sin\theta \, t_{end} \quad [6]$$

$$t_{end} = t_{start}/(\sin\theta) \quad [7]$$

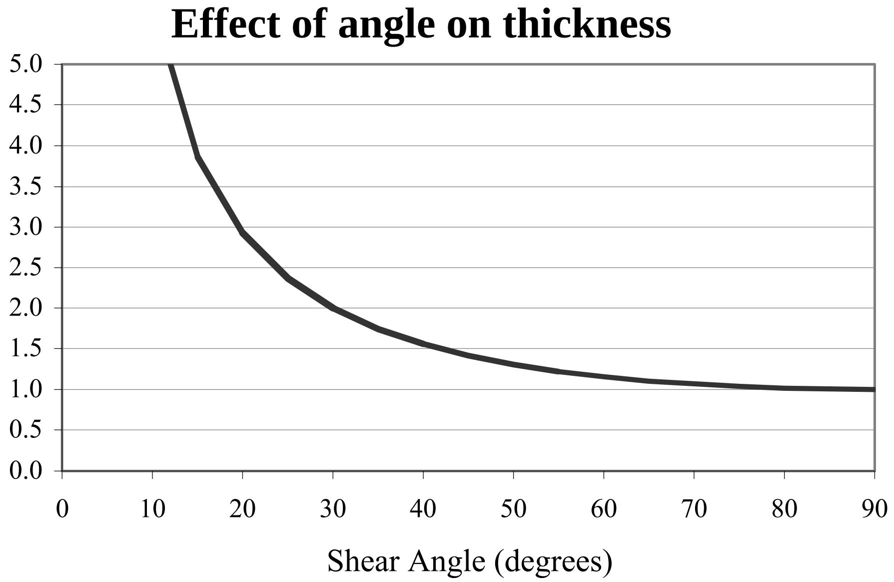


Figure 6. Effect of shear angle on part thickness

This in-plane shear is also known as trellising, and woven fabrics such as the ballistic material used in these experiments have a limit at which point they will bind. Further movement causes the fabric to experience out-of-plane movement such as folding and wrinkling. Fiberforge's efforts to minimize this wrinkling and thickening are described below.

5. PROCESS DISCUSSION

5.1 Blank Design

5.1.1 ***Ballistic shell*** The 9.01 mm (0.355 in.) thickness of the ballistic shell is based on the amount of material required for the level of protection specified by ARL (2). In order to minimize folding and wrinkling, Fiberforge investigated adding cuts and darts to the blank and pulled web tension on the blank during forming. During Fiberforge's experiments, undarted blanks, cut blanks, and darted blanks were all tried. Cut blanks are blanks with cuts made in the blank, but without removing any material. Darted blanks are blanks with material removed from within the part area, as shown in Figure 7. The final design involved significant darting. During forming, the darts would close up so that their edges nearly join together. To avoid having the darts align within the part, the dart was offset ply to ply within the blank. This improved, but did not entirely eliminate, the wrinkling observed in the final parts.

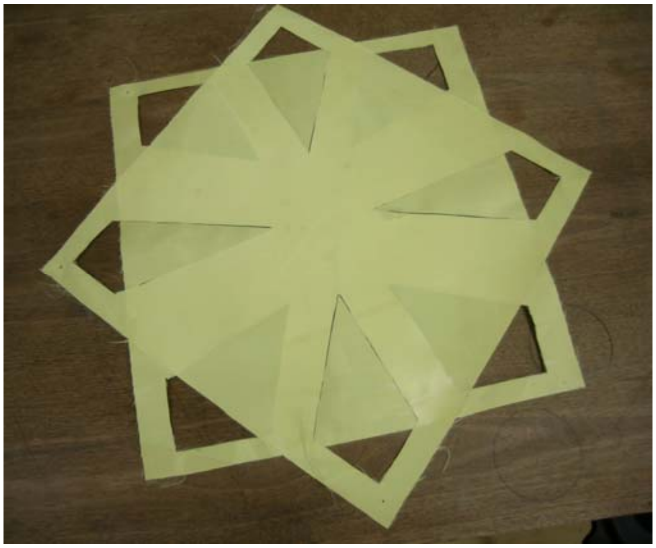


Figure 7. Example of darting

5.1.2 ***Structural shell*** The areal density required for the ballistic materials left enough room in the mass budget for 730–1220 g/m^2 (0.15–0.25 psf) of structural composite. The available carbon/PPS tape has an areal weight of 386 g/m^2 (0.079 psf/ply), which amounted to a maximum of 3 plies of tape.

5.2 Tooling Fiberforge's thermoforming process uses matched molds for forming. During this project, modifications were made to a supplied cavity mold to make it compatible with this process. In addition, a conformable silicone core mold was made using an aluminum mold base and a cast silicone plug (8). Modifications to the cavity mold were minor, and included trimming down the height of the cavity so that the top edge of the mold was closer to the edge of the part, adding vent holes to the crown area of the tool, and adding tool clamp attachments.

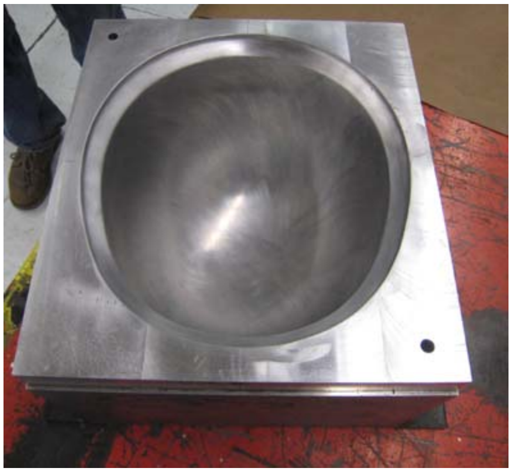


Figure 8. Cavity mold

The cavity was used to cast the silicone core. The silicone was offset by the part thickness using sheet wax.

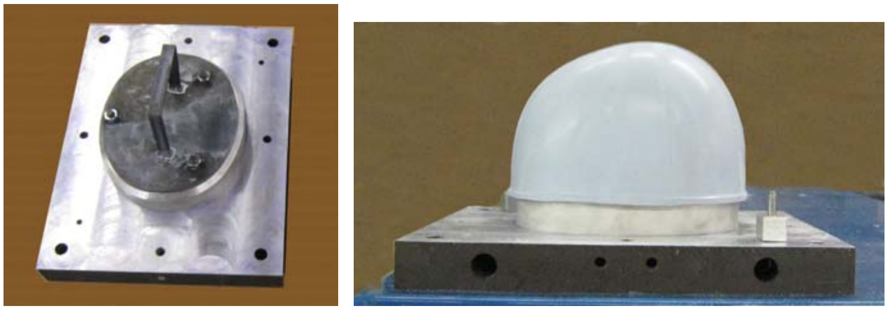


Figure 9. Core mold base (left) and final cast silicone mold (right)

5.3 Fixturing and Heating of Material After several processing and design iterations, Fiberforge chose to co-form the CF/PPS and the aramid in one combined operation. Different amounts of tension and dedicated attachment points were used for the two materials. Since the melting point of PPS is 285 °C (545 °F) and the melting point of the resin in the aramid is 150 °C (302 °F), special heating techniques were employed in order to raise both materials to their respective processing temperatures concurrently. A thermoplastic adhesive was also used between the two components whose melt temperature was between that of the PPS and the thermoplastic in the aramid.

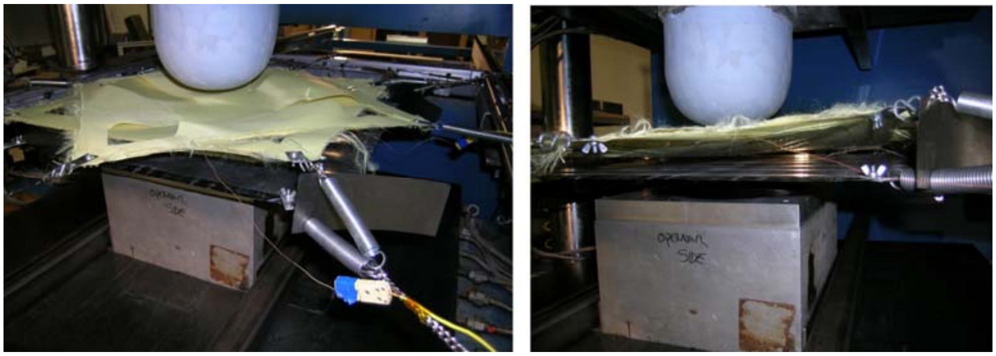


Figure 10. Blank fixturing and alignment of the plies within the press

5.4 Forming Once all of the helmet material reached its processing temperature, a shuttle transferred the blanks to the forming press and pressure was applied until the part had cooled to below 37.7 °C (100 °F). This step took approximately 8 minutes.

This co-forming of a hybrid helmet offers advantages and challenges. Its main benefit is speed: it was faster than forming each part separately, then bonding the shell to the ballistic liner in a subsequent process. However, the strength of the bond between the materials has not yet been quantitatively evaluated, and it remains uncertain how well this technique could be controlled to produce reliable results in serial production. Also, the ballistic performance of these helmets has not yet been quantified.

6. RESULTS

6.1 **Wrinkling** The most significant measure of fabrication quality is the extent of wrinkling of the plies. The first round of hybrid forming had mixed results. The two materials formed together, but the wrinkling of the ballistic material was unacceptably high. The material folded over upon itself, resulting in a 300% to 400% thickness variation around the rim of the helmet. By modifying the darting pattern and clamp tension and location, the thickness variation was reduced to approximately 80%.

Figure 11. Photograph of the initial helmet trial (left) and the final helmet trial (right)

6.2 Process Timing The processing time for each unit operation in the manufacture of the helmets is shown in Figure 12, with discussion following.

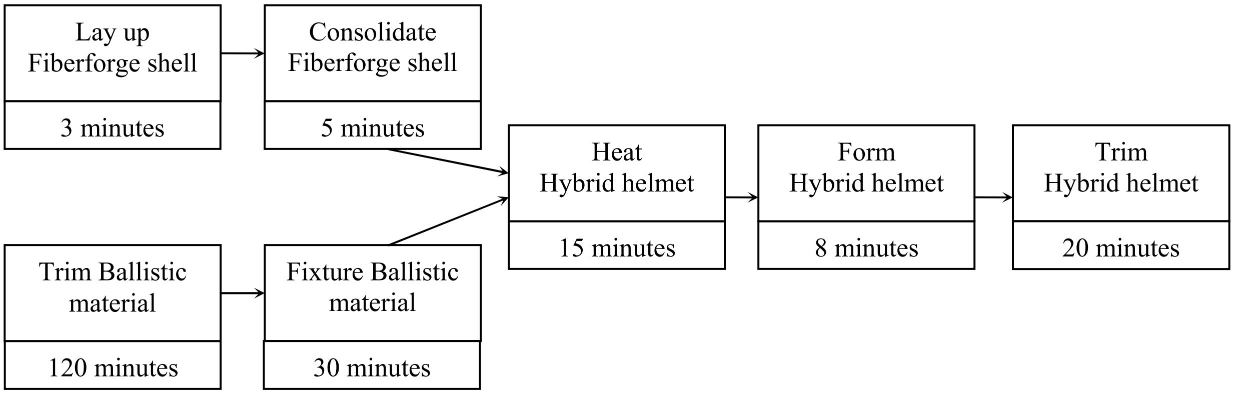


Figure 12. Processing time for each unit operation in the manufacturing process

6.2.1 Layup & Consolidation For this study, Fiberforge used its first generation Relay Station. Since the blanks were made, the Company has released its second generation machinery that operates more than five times faster than the first generation machine. Using this machine would reduce lay-up time to approximately 40 seconds. Consolidation was performed in a hot press, and could be sped up using other more continuous consolidation methods that do not require cycling the tool temperature.

6.2.2 Ballistic Cutting & Stacking The most time consuming process step was hand cutting and fixturing the ballistic material. Manually cutting each of the 39 plies into the correct shape is, however, not a technique that would be used in serial production. Automated cutting and stacking methods should be investigated in future work, as this would benefit both overall processing time and final part consistency and quality, since alignment in the stacking step is crucial for correct final part performance.

In the cutting and stacking step, cutting accounted for 62% of the total time. This operation could be sped up by using flatbed die cutting, rotary die cutting or a NC cutting table. As Fiberforge did not have die cutting or automated cutting equipment available in house at the time of this investigation, these options were not evaluated in depth.

Assembling the ballistic sheets could be accomplished with a dedicated work cell or an automated stacking system.

6.2.3 Fixturing Time Fiberforge's forming system uses an automated shuttle to move material between the IR heating station and the forming press. For prototyping, fixturing is accomplished by drilling holes in the material and manually affixing attachment plates, wires, and springs (as seen in Figure 10). In production, automated grippers and air cylinders to replace the springs would reduce the loading time of each stack from 30 minutes to tens of seconds.

6.2.4 *Heating and Forming Time* Pre-heating the flat blank using IR heating took approximately 15 minutes. One reason for the long heat-up time is that the IR emitters in Fiberforge's thermoforming system are general-purpose ceramic heaters. These work reasonably well for carbon-fiber composites, but the IR frequency range that they emit may not be well suited to heating thick sections of aramid-reinforced composites. IR heaters that emit in the optimal absorption spectrum for a given material can decrease heat-up time by up to 75% (9). If this were the case for the aramid laminate, the overall forming time could be reduced to 4 minutes.

6.2.5 *Forming & Cooling Time* The dwell time in the press was approximately 8 minutes. In this operation, the blank was pressed into shape and held under pressure in an ambient-temperature mold until the material reached 37.7 °C (100 °F). To speed up this step, the tool could be actively chilled to increase the temperature difference between the heated material and the mold.

6.2.6 Trimming Time The formed helmets were manually trimmed using wet saws with diamond coated blades. This operation was very time consuming and would not be appropriate in serial production. Automated cutting methods, perhaps waterjet, ultrasonic, laser, or other cutting technologies should be considered that have been demonstrated to be effective means for cutting thick sections of aramid.

7. CONCLUSIONS

Using innovative layup and forming techniques, Fiberforge was able to show the potential of co-forming the structural and ballistic sections of a hybrid helmet design. With some iteration, the extensive wrinkling seen in the initial forming trials was reduced significantly, with further improvements likely by refining the darting pattern, and tensioning.

The total processing time for these prototype helmets was 201 minutes, with the longest single step being cutting and stacking the ballistic material, at 120 minutes. The most time consuming steps were those that were not automated, such as trimming the ballistic material, fixturing it into a frame for thermoforming, and trimming the formed helmet. These steps could be reduced considerably with automation and selection of more appropriate processes than those used in this initial study. Of the thermoforming process steps, the 15-minute heating time was the longest step. This could be reduced by choosing IR heaters that are tuned for aramid-reinforced composite materials, or by using alternate heating methods. Thus, further work would be required to demonstrate conclusively the benefits of thermoplastic composites in this helmet application.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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