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# PROCESS COMPARISON STUDY
## MSFC Center Director's Discretionary Fund Final Report
## (Project Number 89-03)

By T. Golden and J. Krawiec

Materials and Processes Laboratory
Science and Engineering Directorate

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A process comparison study was conducted using four different advanced manufacturing techniques to fabricate a composite solid rocket booster systems tunnel cover. Costs and labor hours were tracked to provide the comparison between the processes. A relative structural comparison of the components is also included. The processes utilized included filament winding, pultrusion, automated tape laying, and thermoplastic thermoforming. The hand layup technique is also compared. Of the four advanced processes evaluated, the thermoformed thermoplastic component resulted in the least total cost. The automated tape laying and filament winding techniques closely followed the thermoplastic component in terms of total cost; and, these techniques show the most promise for high quality components and lower production costs. The pultruded component, with its expensive tooling and material requirements, was by far the most expensive process evaluated, although the results obtained would not be representative of large production runs.

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## INTRODUCTION

Typically, the selection of a fabrication method for a given composite component is governed by three factors: existing facility and equipment capabilities, economics, and availability of trained personnel. Composites manufacturing equipment is generally highly automated and sophisticated, and varies in cost from several thousand to millions of dollars. As a result, composite component manufacture is not always optimized and cost efficient. Only large corporations can afford to conduct feasibility and trade studies to determine the best methods and to purchase the necessary equipment; smaller companies are usually limited to a "specialty" process. Marshall Space Flight Center (MSFC) is in a unique position in that the productivity enhancement complex (PEC) may be the only single facility in the world with a research and development capability in filament winding, pultrusion, and automated tape laying. This unique capability lends itself to comparative process development and fabrication studies which can yield information to be used industry-wide as a guide for feasibility, trade, and equipment investment studies.

## THE CDDF PROJECT

The purpose of the process comparison study was to compare process development and fabrication efforts for a composite component manufactured using state-of-the-art techniques. The following techniques were evaluated: filament winding, thermoplastic thermoforming, pultrusion, and automated tape laying. The results obtained may be applied throughout industry to enhance the productivity of process selection for composite component fabrication.

A solid rocket booster (SRB) systems tunnel cover (STC) was chosen as the component to be evaluated in the collection of basic design and fabrication data. The STC was selected because its geometry is conducive to all processes under evaluation. It is also a part used in an MSFC managed system which has potential to be converted to a composite component. An 85-percent scale was required as a baseline due to pultrusion equipment limitations.

Due to the unique nature of each process, a direct comparison of the resultant parts could not be made. The design of a given composite part, however, can be changed fairly easily to accommodate the process and still meet component specifications. For example, the filament winding machine is incapable of winding the 0° plies required for the STC, while the pultrusion machine requires 0° plies to pull the component through the die. For this process comparison study, the STC was designed to each manufacturing technique to accommodate these types of limitations and to optimize the processability.

Fabrication and testing support for this study was provided by Thiokol Corporation Space Operations, MSFC Advanced Programs and Technology. Additional assistance was provided for the pultrusion portion of the study by University of Mississippi students.

## PROCESS COMPARISONS

The summary of costs for each of the advanced manufacturing methods evaluated is presented in table 1. In addition to the four state-of-the-art processes, costs are also presented for the hand layup technique. Although the manual method is widely used to eliminate the costs of automated processing equipment, it is more time consuming and is often less repeatable. The costs for the hand layup technique included materials (Hercules graphite fabric/epoxy AW370-5H/3501-5A); tooling (Toolrite System: MXG-7620/2534 graphite fabric, MXG-7620/2548 graphite fabric, MXG-7620/2577 graphite fabric, and MXR-7675 surface gel coat); and, labor as presented in table 1.

### Filament Winding

For filament winding, a male winding mandrel was designed to produce two back-to-back parts. This tooling concept represents the most efficient design for the filament winding process. The laminate design required 0° unidirectional plies. Since it is not possible to automate the placement of the 0° plies with the filament winding process, these plies, or tapes, were made using a hot melt prepregger, followed by B-staging for 4 to 5 days to lower the tack and to vent volatiles. Graphite fibers and epoxy resin were then wet wound using the five-axis Entec winder and associated software with hand placement of the 0° tapes. Following winding, the part was vacuum bagged and oven cured. After cure, the part required machining to separate and remove the halves from the mandrel and to trim to the final part dimensions.

Of the advanced processes evaluated, MSFC and Thiokol personnel have the most experience in filament winding. This is demonstrated in table 1 by the amount of process development time required for the filament-wound STC as compared to the other advanced methods. Two different ply layup designs were utilized for filament winding because the first design resulted in high spring-back and part thickness. The second ply layup design improved the thickness, although some spring-back occurred and the part surface quality was not optimal. The material cost shown in table 1 is representative of a single-ply layup design (one set of back-to-back parts).

The major cost driver for the filament-winding process was that of tooling. This tooling consisted of the single male mandrel which required 87.5 h of design time and cost $6,235.00 to fabricate. The mandrel is reusable, however, and produces two components for each winding. The material cost for two parts (one winding) included the Hercules AS4/12K graphite fiber tows ($700.00), the Shell 9405/9470 epoxy resin ($50.00), release film and fabric ($245.00), and vacuum bagging materials for the oven cure ($100.00).

As illustrated in table 1, an average fabrication time of 38.5 h was required for the two different ply designs (the first set required 39 h and the second set 38 h). This fabrication time included actual part fabrication (56 h for both designs), oven preparation and curing (16 h for both designs), and part trimming (5 h for both designs). A significant amount of the fabrication time consisted of manufacturing the unidirectional prepreg tapes for the 0° plies. This approach offset the cost of procuring prepreg tows, although vendor-supplied prepreg tapes are usually of higher quality.

The filament-winding process is generally a relatively inexpensive process, although for some designs, as with the STC, hand processing is required to place 0° plies. This problem could be solved by employing fiber placement equipment. This type of process is capable of total component layup using automated methods. Although unavailable during the course of this study, MSFC now has automated fiber placement equipment at the PEC.

## Thermoplastic Thermoforming

The approach undertaken to fabricate the thermoplastic STC consisted of rough forming graphite/polyphenylene sulfide (PPS) tape into the female half of an existing pultrusion die. (The pultrusion die was used as the forming fixture to control study costs.) A paint stripper heat gun and a metal roller were utilized to form the plies into the part radius as well as to adhere each successive ply during the layup. The part was then consolidated in a high-temperature autoclave.

As table 1 indicates, the thermoformed thermoplastic STC was relatively inexpensive to fabricate, although development time was fairly extensive. A developmental forming process was first attempted in which the material was rough-formed (hand layup technique) then heated via the pultrusion die platens. Unfortunately, these platens did not supply enough temperature to form the part. As a result, the high-temperature autoclave was required. The autoclave forming process supplies the required heat and pressure, but is more time consuming than using a high temperature platen press (which was unavailable).

To control study costs, the actual tool used to form the thermoplastic part was the female half of the pultrusion die. The more realistic choice for this process is a simple mold. In order to present a more realistic cost for this study, a simple mold was designed and a bid was solicited. As presented in table 1, the design time for this mold was 16 hours with a bid cost of $800.00.

Material cost for the thermoformed thermoplastic STC included the thermoplastic material, Phillips 66 Ryton PPS ($1,100.00); and, vacuum bagging materials for the autoclave cure ($280.00). The fabrication hours presented in table 1 include actual fabrication (20 h), part consolidation (24 h), and final machining (3 h).

Thermoplastic thermoforming represents a viable process. For this study, graphite/PPS was chosen for comparison with the materials used for the other advanced processing techniques. When thermal protection is a requirement, a material such as polyether etherketone (PEEK) may be used. With a thermoplastic material, the scrap amount can be very low once the process is optimized, although processing the high-temperature thermoplastic materials requires an investment in specialized capital equipment. In addition, with the higher temperatures, operator safety is a concern, and the process may require automation.

## Pultrusion

For pultrusion, stitched graphite fiber/fabric and epoxy resin were pultruded using the Pultrusion Technology, Inc., Pulstar 1612 with the existing die and procured accessories. Significant development time was required due to the expected force required to pull the part through the 3-ft long steel die. The STC has a large surface area with respect to fiber volume which could over stress the fibers should the pulling/friction forces become too high. As a result, a stitched fiber/fabric was selected due to the difficulty in pultruding off axis (non-0°) plies and for strength to withstand the pull forces.

The part was originally designed at 60-percent fiber content, consisting of eight plies of graphite fiber fabric oriented as follows: $[0,-45,+45,90]_s$. Due to the poor "as received" condition of the material, two separate processing runs were performed. In the first, both the 0° ply and the 90° ply were removed to avoid using shims and the possibility of hanging the part in the shim area. The resultant part visually indicated excessive resin and exhibited a low fiber content of 45 percent. On the second run, only the 0° ply was removed and the clay filler in the epoxy matrix was decreased to promote better wetting/resin flow. The resultant part from the second run yielded a more visually acceptable appearance with a fiber content of 53 percent. On both runs, some difficulty was experienced in keeping the graphite fabric material aligned while pulling it through the die.

The pultruded component was by far the most expensive as indicated in table 1. The primary drivers consisted of the tooling and the material. The tooling requirements included a steel die ($12,380.00), pullers ($4,490.00), shims ($350.00), a preform guide plate ($843.00), and a resin bath ($2,700.00). An existing die, which required some rework, was utilized for this project. The cost of the rework was not included as a cost in this study.

Material cost included the Hexcel graphite stitched ASG4 fiber/fabric ($3,444.00) and the epoxy matrix ($437.00) which consisted of Epon DPL 9420 resin, Axel Int 18-46 lubricant, Epon 9470 curing agent, Epon RSM 537 accelerator, and Kaolin ASP 400p clay filler.

The fabrication time presented in table 1 is also fairly substantial. Considerable process development work was required, using expensive materials. However, once the pultrusion process is developed and the machine is setup, it could be competitive for high volume production with minimal wastage. Long continuous parts can be produced at a rate of approximately 1/2 to 2 ft per minute. One advantage to pultrusion is that there is no autoclave or other costly postprocessing cure requirements.

## Automated Tape Laying

For the STC fabricated using the automated tape laying process, the ten-axis Cincinnati Milicron automated tape layer was utilized to lay 3-in graphite/epoxy prepreg tape onto a flat plate. The laminate was then placed upon the male half of the pultrusion die (used as a hot drape forming tool for this process). Utilizing a forming fixture, the laminate and forming mandrel were then vacuum bagged and the laminate heated using an infrared heater. Once heated to 140 to 150 °F, vacuum was drawn on the assembly to form the laminate. The formed laminate was then trimmed to fit the female curing tool (the female mold which was used for the STC fabricated employing the hand layup technique), and vacuum bagged for autoclave cure.

For the automated tape laying process, the pultrusion die (the male half) was again used to control study costs. Again, the more realistic choice for the process is a simple mold. A female mold was also required for use as a forming tool. The cost for the process tooling shown in table 1 included only the simple mold since the forming fixture was fabricated using surplus materials for which material costs were difficult to estimate but presumed to be minimal. Component material cost included the Hexcel F584 prepreg tape ($1,316.00), release film and fabric ($138.00), and vacuum bagging materials for the autoclave cure ($105.00). Fabrication time includes actual part fabrication (24 h), part forming and cure preparation (17.5 h), autoclave curing (20 h), and part trimming (2 h).

The automated tape layup/hot drape forming process was found to be a very viable process. In a production environment, this process should result in little scrap, but would incur some capital equipment investment.

## STRUCTURAL COMPARISONS

Flexure testing was selected for this study as appropriate for the loads induced on the STC both during SRB flight and splashdown. As a representative test, ASTM D790 flexure was selected because it loads the samples in a combined tension and compression mode. A total of six samples were tested for each fabrication method evaluated under this study. These samples included three 0° (longitudinal, or along the length of the STC) samples; and, three 90° (perpendicular, or across the width of the STC) samples. A sample size of 3 by 0.5 in was selected for three-point load testing on a 2-in span. A loading rate of 0.05 in/min was used. The summarized test results are presented in table 2.

The flexure test data provided some relative indications regarding process selection; and, although the ply design for a given composite component would necessarily have to be based on the actual stress analysis data, the flexure test data also provided some indications regarding the ply design for each process.

The difficulty in obtaining an optimum layup for the filament-wound component was evident in the variation between the 0° and 90° test samples, as illustrated in table 2. These samples also failed in interlaminar shear which indicates the need for an improved ply design and possibly a better epoxy resin. The thermoplastic part lost its vacuum bag when it was at the forming temperature which could have affected the part consolidation and hence the test results. The results favor the 90° samples which may indicate a need to improve the ply design. The difficulties encountered during the pultrusion process are reflected in the low strength data as shown in table 2. The test samples exhibited failure at the fiber layers that were not adequately wetted out. The STC fabricated using the automated tape laying process exhibited the best strength results, and the test data show a good balance between the 0° and the 90° test orientations.

## SUMMARY

The most cost effective method evaluated was the hand layup technique as illustrated in table 1; however, it should be noted that the STC was relatively simple to hand lay and the technician has extensive experience. For one-of-a-kind parts with simple geometries, the manual fabrication method is the best choice, especially when capital outlays for automated equipment are considered. However, most aerospace components require high quality and special materials for strength properties; and high quality, cheap parts are difficult to obtain using totally manual methods.

In comparison with the other advanced processes evaluated, filament winding proved to be relatively easy and inexpensive. The experience level of the personnel involved in this portion of the study is evident in the low level of process design and development time required. The tooling represented the largest expense for this process; however, the mandrel is reusable and produces two components for each winding.

Overall, the thermoformed thermoplastic STC was also relatively inexpensive; however, the process design and development time was considerable. The "boardy" nature of the thermoplastic material and the high temperatures required to adhere the plies during layup were the major drivers.

The pultruded STC was the most expensive component evaluated in this study. The tooling was the largest cost driver, although material costs and process development and fabrication times were also comparatively large. The type of component, the STC, may have contributed to the end result: most pultruded components do not require the ply orientations of the STC. Once the pultrusion process is set up for a particular design, a very high rate of production is feasible, which would lower the cost.

Automated tape laying compared favorably with the other advanced methods evaluated. The large design and development time represented in table 1 was primarily due to programming requirements and experience levels. Since this process cannot lay up the net geometry of the STC, development of the hot drape forming process was required. The overall process did produce the highest quality part of the advanced processes evaluated.

Overall, this process comparison study was very informative. In composite manufacture, part geometry and design requirements generally narrow down the viable process options. Relatively simple geometries like the STC, however, lend themselves to a number of potential processes. This project revealed how five different processes actually compare. Other factors, as demonstrated in this project, can also influence the choice of the "best" process including experience, tooling availability, equipment availability, material availability, and design requirements.

Table 1. Summary of costs.

| Process | Process Design and Development (hours) | Tool Design (hours) | Tool Cost ($) | Component Materials ($) | Component Fabrication (hours) | Total[a] Cost ($) |
|---|---|---|---|---|---|---|
| Hand Layup | 16 | 4 | 936 | 1,070 | 50 | 5,156 |
| Filament Winding | 30 | 87.5 | 6,235 | 1,095 | 38.5 | 14,350 |
| Thermoplastic Thermoforming | 157 | 16[b] | 800[b] | 1,380 | 47 | 12,080 |
| Pultrusion | 169 | 364 | 20,763 | 3,881 | 137 | 54,794 |
| Automated Tape Laying | 160 | 20[c] | 800[d] | 1,559 | 63.5 | 13,316.5 |

a. Based on an arbitrary $45.00/h.
b. Designed/costed forming tool (see discussion in thermoplastic thermoforming section).
c. Includes designed/costed forming plus drape tool (4-h design).
d. Does not include drape tool cost (see discussion in automated tape laying section).

Table 2. Summary of composite flexural data.

| Process | Sample Type | T (°F) | Failure Load (lb) | | Failure Strength (lb/in$^2$) | | Failure Mode |
|---|---|---|---|---|---|---|---|
| | | | Mean | SD | Mean | SD | |
| Filament Winding | 0° | 80.3 | 70.20 | 6.99 | 58,634.77 | 3,905.39 | Interlaminar Shear |
| | 90° | | 187.10 | 8.50 | 158,242.09 | 8,580.64 | Interlaminar Shear |
| Thermoplastic Thermoforming | 0° | 79.7 | 63.13 | 3.57 | 73,725.79 | 3,968.93 | Interlaminar Shear |
| | 90° | | 93.00 | 18.47 | 106,188.47 | 11,066.12 | Interlaminar Shear |
| Pultrusion | 0° | 79.4 | 172.13 | 40.75 | 74,528.81 | 16,936.87 | Bonding (Dry fibers) |
| | 90° | | 52.60 | 14.53 | 25,481.64 | 8,273.74 | Bonding (Dry fibers) |
| Automated Tape Laying | 0° | 79.7 | 185.57 | 10.17 | 182,875.88 | 11,506.09 | Interlaminar Shear |
| | 90° | | 177.43 | 1.03 | 181,541.37 | 5,125.76 | Interlaminar Shear |

## APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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