

NASA'S COMPOSITE OVERWRAP LESSONS LEARNED ON 40K THRUST CHAMBER ASSEMBLIES

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ABSTRACT

Filament wound carbon fiber/polymer composite overwraps combined with additively manufactured (AM) copper alloy combustion chambers are a critical part of NASA's Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project. The composite overwrap is a high strength-to-weight material and allows for significant weight reduction of the high-pressure thrust chamber assembly, reduction of overall cost, and reduced fabrication time while offering structural robustness. Integrated AM/composite overwrap chamber assemblies using 907 kg (2,000 lbf (2k)) and 3200 kg (7,000 lbf (7k)) thrust were successfully hot fire tested at NASA Marshall Space Flight Center (MSFC). These assemblies allowed the team to learn lessons related to the design, analysis, and manufacturing of these integrated assemblies. A final goal of the RAMPT project is to design and test a 18100 kg (40,000 lbf (40k)) thrust chamber assembly. The 40k chamber presented the team several new challenges including an integral inlet port in the main body of the composite overwrap. Through multiple iterations of manufacturing techniques, varied materials, and Non-Destructive Evaluations (NDE), many lessons were learned to obtain a final design solution that would not only allow for the interrupted port inlet but also allow for sufficient material margins for the most critically stressed part of the chamber. This paper will cover the manufacturing techniques exploring fabric designs to help subsidize the coverage in the areas left bare by the inlet port during the filament winding process and custom tooling needed for the final full chamber processing. The original material choice of bismaleimide (BMI) 5250-4 from the 7k chamber performed well for the extreme environment of hot fire testing but proved to be difficult with the increased scale and interrupted port design of the 40k chamber. Discussion in this paper will cover these changes, including evaluation of the design, comparison to the prior 2k and 7k designs, and show the final hardware that will be tested. One primary goal of this work and RAMPT project is to provide this development process and data to industry for infusion into future engine designs.

Keywords: Filament Wound, Composite Overwrap, Lessons Learned, Manufacturing Techniques, Rocket Engine, Thrust Chamber Assembly

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1. INTRODUCTION

The goal of the NASA's Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project is the maturation of novel design and manufacturing technologies to increase scale, significantly reduce cost, and improve performance for regeneratively-cooled thrust chamber assemblies (TCA); specifically, the combustion chamber and nozzle for government and industry programs [1]. An overview of the key technology developments within RAMPT is presented in Figure 1 and includes additive manufacturing (AM) of novel copper alloys (GRCop-42), large scale AM using directed energy deposition (DED), bimetallic AM, and composite overwrap. RAMPT builds upon technologies developed under NASA's Game Changing Development Program's Low Cost Upper Stage Propulsion (LCUSP) project as well as on other technology development projects [2-3]. Manufacturing technologies developed under LCUSP included AM Laser Powder Bed Fusion (L-PBF) of Copper Alloy GRCop-84 and Electron Beam Free Form Fabrication (EBF3) with Nickel Alloy Inconel 625 to produce a rocket combustion chamber within a shorter schedule and at a lower cost [2].

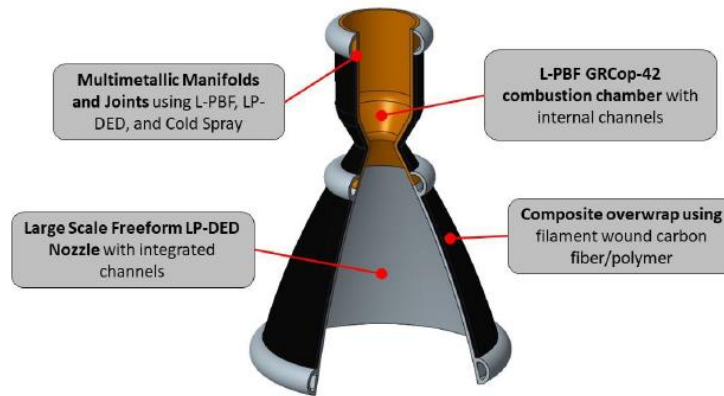


Figure 1. Overview of Manufacturing Technologies within the RAMPT Project

The channel cooled liner for the RAMPT project is produced by L-PBF of Copper alloy GRCop-42 (Cu-4 wt.%, Cr-2 wt.% Nb). Copper alloys are desirable for chamber liners due to their high thermal conductivity, which allows for effective wall cooling to maintain structural yield strength and fatigue life margins at elevated temperatures. Prior developments using high pressure AM chambers have required the use of a bimetallic structural jacket, fabricated using an Inconel 625 alloy. The RAMPT project has proposed and developed composite overwrap for structural support of the chamber liner. Composites offer much higher strength-to-weight ratio than the traditional metals utilized for structural support in chambers. It is anticipated that the LCUSP developed ability to produce closed channel GRCop alloy liners along with the advances in composite overwrap fabrication will allow the chamber to meet weight, schedule, and cost saving goals.

Composite manufacturing throughout the RAMPT project has proceeded under a public-private partnership with Auburn University and Kord Technologies® with the goal of maturing design and manufacturing technology within the industry. The critical functions of the composite overwrap include: enabling significant weight reduction of the chamber assembly, reducing overall cost and manufacturing schedules, and reducing distortions in the chamber caused by prior bimetallic cladding. Throughout this program, many lessons were learned with respect to the composite

overwrap as a structural jacket for the chamber such as material performance over broad thermal requirements, manufacturing process development, surface preparation, and tooling configurations. The processing techniques and lessons learned have been applied to filament winding over varying scales of thrust chamber hardware.

The purpose of this paper is to detail manufacturing processes and lessons learned throughout the fabrication of the largest RAMPT 40k chamber composite overwrap for high temperature-high pressure metallic thrust chambers. Material performance requirements, manufacturing process development, and surface preparation were evaluated during the smaller chamber trials, with the broad thermal requirements of the resin being the primary driver for material selection and processing [3]. Both epoxy and bismaleimide (BMI) materials were evaluated with respect to both performance in the hot-fire test and ease of fabrication. The 40k chamber trials based the lessons learned from the smaller chambers applied into the larger configuration. Noteworthy changes included incorporating the EPON[®] 828/W epoxy matrix resin for ease of processing, the inlet port hole interrupting overwrap continuity, and implementing new tooling designs, which will be discussed.

1.1 Application

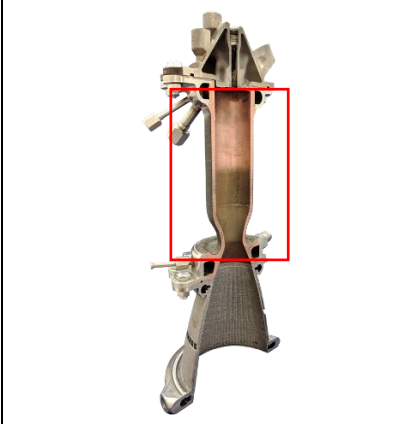
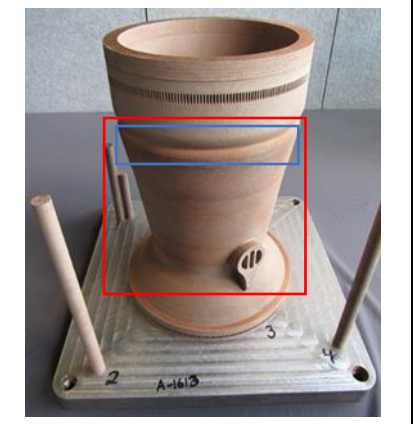
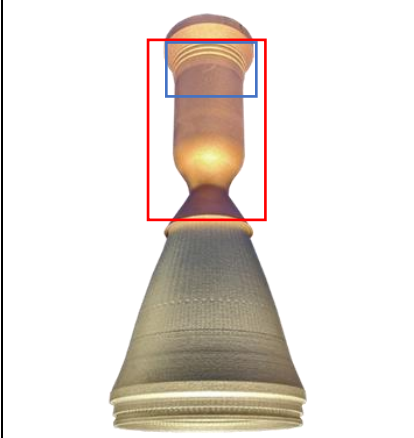
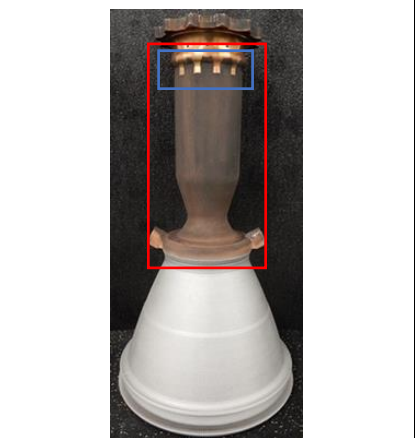
Rocket engine combustion chambers provide volume for the propellants (fuel and oxidizer) to mix, vaporize, and combust. They serve as structural components to contain the pressure of combustion that is converted to high velocity flow, creating thrust as the gas is expanded through a nozzle. NASA and industry partners have realized the benefits of the high strength-to-weight that composite overwrap technology offers in tanks and pressure vessels and extended this development to combustion chambers and nozzles. Replacing comparatively lower strength-to-weight metals currently utilized for structural jacket in combustion chambers with the composite overwrap offers the potential to decrease weight up to 50%. Two recent technology advancements allow composite overwrap structural jackets to trade more favorably than in the past. First, advancements in additive manufacturing laser powder bed fusion (L-PBF) technologies with GRCo alloys allow combustion chamber liners to be printed with closed-out channels presenting a solid surface to wrap around. Traditional chambers would have milled channels that had to be closed out, and the closeout material was often a metal that also served as the structural jacket. Chambers and nozzles that utilize propellants to convectively cool the walls that are in contact with the hot gas are known as regeneratively cooled chambers and nozzles. The convective cooling maintains the metal temperature where the metal still has strength when hot gas temperatures in the chamber can exceed 2760 °C (5000 °F). The temperature profiles along the outer surface of the liner to composite interface are similar to the bulk coolant temperature at an axial location and can span from cryogenic [-200 °C (-328 °F) in the case of liquid hydrogen] to temperatures of 232 °C (450 °F) and greater depending on the fuel type and engine cycle. The composite must maintain functionality at the liner to composite interface temperatures. There are several challenges with the composite technology that require considerable process development and characterization. These include optimization of the bond between the metallic and composite material, the directional strength of the composite overwrap material, the complex geometry for composite fabrication and the material performance under the intended use environments. Composites for chambers also offer benefits in addition to weight reductions when compared to other additive

chamber jacketing techniques since the processing temperature is much lower than that of metals, greatly reducing the residual stresses and associated warping left in the final part.

1.2 RAMPT Hardware Overview

The various sizes of hardware for the composite overwrap are shown in Table 1-1. The areas of red indicate where the composite overwrap covers the chamber. Ridges have been printed directly into the chamber in order to provide an anchor for the helical and hoop wraps as seen in the blue boxes.

Table 1-1. Various Thrust Classes of RAMPT Chambers being Developed

2k-lbf Decoupled LOX/RP-1	7k-lbf Decoupled LOX/LCH4	40k-lbf Coupled LOX/LH2
		
2k-lbf Coupled LOX/LH2	7k-lbf Coupled LOX/LCH4	40k-lbf Decoupled LOX/LH2
		

**Red indicates areas where composite overwrap is applied, and blue is the forward ridge for anchoring.*

With the chamber experiencing mainly hoop/burst pressure loads while holding secondary axial loading, the overwrap essentially acts similar to a composite overwrapped pressure vessel (COPV). Therefore, multiple winding patterns were evaluated based on the unique loading requirements of the chamber. Surface preparation procedures were evaluated during smaller chamber designs to inhibit bonding between the chamber and overwrap [3].

The 40k-lbf coupled and decoupled are the focus of this paper. The biggest challenge with the 40k coupled chamber is the inlet port protruding element that prevents a flat winding surface as seen in the 40k coupled photo in Table 1-1. The wind pattern is required to go around the port since it is in an area of high stress on the chamber during hot-fire based on stress analysis. To provide more strength to the open areas left by the port hole after winding, prepreg fabric was inserted in between the filament wound layers. Information regarding the entire manufacturing process for the 2k, 7k, and 40k chambers can be found in “Maturation and Hot Fire Testing of Additively Manufactured Bimetallic Composite Overwrap Thrust Chamber Assemblies” [5]

2. MATERIAL REQUIREMENTS

The material thermal requirements varied among the 2k, 7k, and 40k chambers. The higher temperature range experienced by 7k chambers during hot-fire test drove initial resin selection for the 40k and the desire to maintain similar materials. For example, the temperature on the outside of the 7k-lbf chamber in steady state operation spanned from cryogenic -157 °C (-250 °F) at the coolant inlet near the throat to 204 °C (400 °F) at the coolant outlet at the forward end of the chamber. The large temperature gradient and rapid heating/cooling cycles of startup and shut down could lead to high stresses on the composite and ultimately micro-cracking of the resin and/or delamination of the overwrap. Therefore, the team chose to have an unbonded overwrap. To accommodate both the upper and lower temperature extremes, Solvay CYCOM® 5250-4 toughened bismaleimide (BMI) resin was selected for manufacturing development. Manufacturing for the 2k chamber overwraps used EPON® 828/W toughened epoxy (and BMI 5250-4 in later trials) as the overwrap experienced temperatures ranging from room temperature to 121 °C (250 °F). The 2k and 7k manufacturing methods are discussed in a previous CAMX paper [3]. Additional, 2k decoupled work, including hot-fire testing was published in Protz et al. [1] and Gradl et al. [4]. For the 40k development, the team’s desire was to keep the BMI material, but due to manufacturing challenges eventually switched back to the EPON® 828/W epoxy matrix.

2.1 Testing Requirements

The 40k chamber uses liquid oxygen/liquid hydrogen (LOX/LH2) propellants and the temperature range is -240 °C (-400 °F) to 66 °C (150 °F). The internal combustion chamber pressure will be approaching 11,031 kPa (1,600 psig). The composite overwrap will need to be able to withstand cycling with these ranges for the hot-fire testing to be successful.

2.2 Fiber

IM7G, 12K tow carbon fiber from Hexcel® was selected because of advantageous mechanical properties, experience with the fiber from previous chamber builds, and its availability at the start of the project.

2.3 Resin

EPON® 828 epoxy combined with curing agent W was selected after the trials with the BMI for ease of manufacturing and versatility. When cured, this resin has good mechanical, adhesive, and

chemical resistant properties. Although the 828/W matrix was ultimately selected, resin material characterization of both the 828 and 5250-4 resins were evaluated and will be documented in future works. These studies looked at tests such as dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC) for both resin systems.

2.4 Surface Prep

Prior to filament winding, all chamber surfaces are polished with aluminum free 80 grit then 120 grit sandpaper to remove surface roughness and oxidation. The surfaces are washed clean with ethanol then treated with multiple coats of Frekote NC700 mold release agent [3].

3. MANUFACTURING PROCESS DEVELOPMENT WITH 5250-4 BMI

The composite overwrap was manufactured with a 4-axis filament winder using between 1.8 – 3.6 kg (4-8 lbf) of tension. After multiple dry winding trials on a foam mandrel and data from stress analysis, it was determined that a layup of at least three layers of prepreg and 0.15 cm (0.06-inch) thick overwrap was required. The inlet port that causes the discontinuities in the fiber leaving gaps around the chamber is where the majority of manufacturing development was focused. Prior experience was focused on wound parts with a continuously smooth surface and not the discontinuity of ports or other protruding features. Custom designed prepreg was required to cover these areas lacking in hoop wrap around the port hole.

3.1 IM7 Prepreg

Using a CAD model of the 40k chamber, custom pieces of prepreg fabric strips were cut out using a Gerber cutting table to wrap around the port hole (Figure 2). They were made slightly longer than were required to be. This allowed a custom angled butt joint fitting after winding on the chamber since the chamber gets thicker after each overwrap layer. Originally the pieces were cut to be the same exact size, but after iterations it was determined that they edges needed to step down in width from piece to piece. This helped the outer mold line not have a drastic drop in the middle of the chamber. Initially, the step off was manually cut and then eventually programed into the original cut diagram as seen in Figure 3.



Figure 2. IM7/8552 Prepreg Custom Shapes

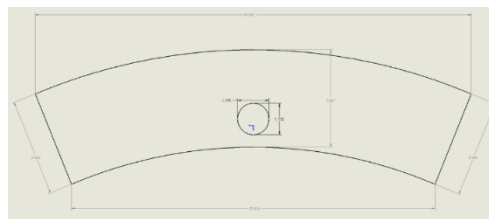


Figure 3. Cut Diagram

All the prepreg in these trials were made from IM7G/8552 fabric rolls. Figure 4 shows the step offs in the prepreg.



Figure 4 Prepreg Dimensional Changes

3.2 Chamber Trial 1

A high temperature practice foam mandrel was fabricated using the CAD model of the 40k chamber and prepped with Teflon tape as seen in Figure 5 A to keep the resin from bonding to the foam. This was done so the team could use the foam mandrel multiple times for practice trials before moving to a metallic chamber. The layup schedule for this trial started out as ([fiberglass][+90][prepreg][-90][prepreg][+90][prepreg][-90]). A layer of the 5250-4 BMI resin was then applied first as a base coat along with the small piece of fiber glass around the port as seen in Figure 5 A. The viscous resin was heated to 82 °C (180 °F) to become thin enough for hand application, but prior to any the onset of resin cure. The team used a hand layup method due to the fact the resin would bead up and become too viscous too quickly from the resin bath to the part if the winder's resin carriage was used.

(([fiberglass][+90][prepreg][-90][prepreg][+90][prepreg][-90]))

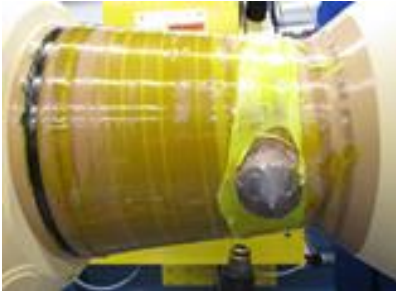


Figure 5 A. Resin/Fiberglass Layer



Figure 5 B. Hoop Layer 1

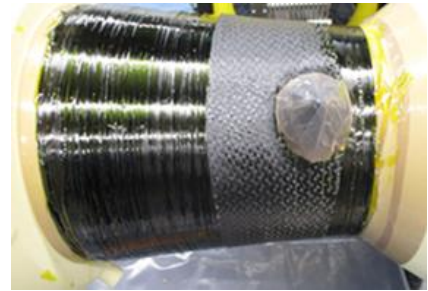


Figure 5 C. Prepreg Layer 1

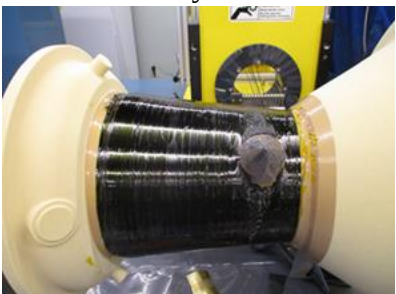


Figure 5 D. Hoop Layer 2



Figure 5 E. Butt Joint Cut



Figure 5 F. Final Hoop Layer

Figure 5. Trial 1 Layup Process

Figures 5 A-D show the first couple of layers of composite starting with the +90 degree hoop layer. This is followed by the first layer of prepreg and the -90-degree hoop layer. Figure 5 E shows how the prepreg was cut at an angled butt joint to fit the overwrap which was done for all prepreg pieces. Each layer of prepreg was cut at a different angle as well to keep any discontinuities from stacking. Figure 5 F is the last two layers of the prepreg and hoop wraps before shrink tape was applied.

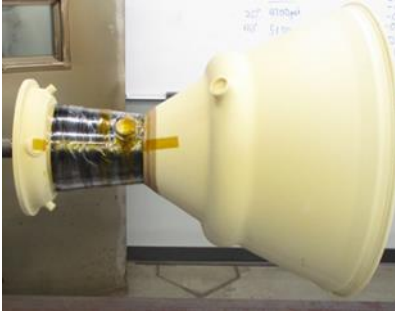


Figure 6 A. Final Part Before Cure



Figure 6 B. After Cure



Figure 6 C. Wrinkling in Prepreg

Figure 6. Chamber Post Manufacturing

For this first chamber trial, only a single layer of shrink tape was applied to entire composite and preshrunk before oven curing. After cure the chamber was satisfactory, except for the area around the port. The prepreg pieces ended up wrinkling in the exposed regions and there was resin pooling around the port hole.

3.2.1 Lessons Learned from Chamber Trial 1

The main take away from trial 1 was that the team needed a better tooling system besides shrink tape alone to keep the fabric from wrinkling. While adding fabric in between wet wound layers is not a novel idea, usually they are fully covered after. The hoop wraps squeezed the prepreg causing them to buckle in the open regions when the resin reached low viscosity during oven cure.

3.3 Chamber Trial 2

Trial 2 had similar manufacturing steps as trial #1 with the additions of more hoop wraps to meet the 0.06-inch-thick minimum requirement and a silicone caul plate to aid in compaction and resin consolidation around the port region. The layup schedule changed from trial #1 to ([fiberglass][+90][pre-preg][-90][pre-preg][+90][pre-preg][-90][+90]fwd-end[-90]fwd-end) in trial #2. An additively manufactured L-PBF 40k manufacturing demonstration piece was also used for this trial instead of the high temperature foam.

(([fiberglass][+90][pre-preg][-90][pre-preg][+90][pre-preg][-90][+90]fwd-end[-90]fwd-end)

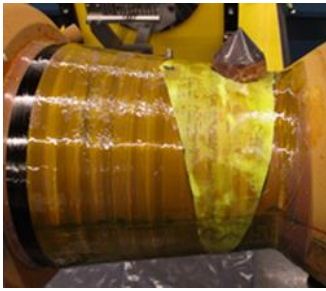


Figure 7 A. Resin and Fiberglass



Figure 7 B. First Hoop Layer

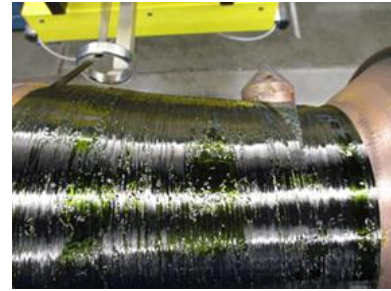


Figure 7 C. Second Hoop Layer

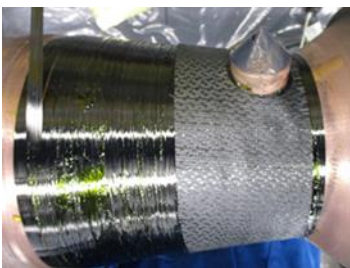


Figure 7 D. Second Prepreg Layer



Figure 7 E. Fourth Hoop Layer

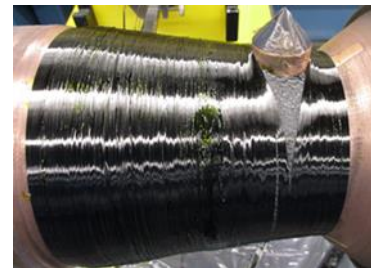


Figure 7 F. Final Hoop Layer

Figure 7. Trial 2 Manufacturing Process

A layer of resin was still added to the chamber first along with the fiber glass layer. Figures 7 A-F show various stages in the layup with Figure F being the final wrap before the shrink tape layer. The filament winding process was essentially the same as the first trial but added hoop layers to the part. Along with shrink tape, a silicone caul sheet was made to wrap around the part during cure to help with the wrinkling. However, this still did not provide enough pressure to keep the prepreg from wrinkling in the exposed areas.



Figure 8 A. Shrink Tape Application

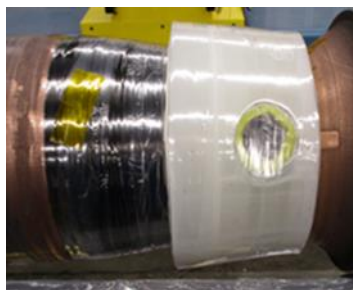


Figure 8 B. Silicone Caul Sheet



Figure 8 C. Final Part

Figure 8. Trial 2 Tooling

3.3.1 Lessons Learned from Chamber Trial 2

It was hard to control resin application with it being too viscous at room temperature. With further improvements to techniques and modifications to machinery, the team believes it can be done, but in the interest of time to the project, the team decided to switch back to the 828 epoxy resin. For the wrinkle control, a soft caul plate was not enough to keep the ridges from forming in the prepreg; something more ridged needed to be added.

4. MANUFACTURING PROCESS DEVELOPMENT EPOXY 828

The 40k manufacturing demonstration was sent back to MSFC where the team decided to switch to the 828/W resin matrix combination to help ease manufacturing difficulties and have better resin control overall.

4.1 MSFC Chamber Trial 3

It was decided to begin with the prepreg as the first layer in the composite matrix and eliminate the fiberglass layer.

[(pre-preg)[+90][pre-preg][-90][pre-preg][+90]]



Figure 9 A. First Prepreg Layer

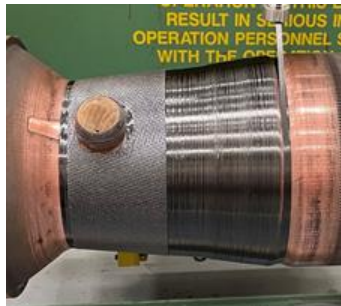


Figure 9 B. First Hoop and Second Prepreg Layer



Figure 9 C. Second Hoop Layer



Figure 9 D. Final Prepreg Layer



Figure 9 E. Final Part Before Cure

Figure 9. Trial 3 Manufacturing Process

The main goal of this trial was to improve the tooling technique, so the extra hoop layers added in trial #2 were not added in this trial. Figure 9 A shows an example of the prepreg on the bare chamber. Figure 9 B-E shows some the subsequent layers outlined in the layup design of

([pre-preg][+90][pre-preg][-90][pre-preg][+90])). For the first two trials, a gap was observed around the port hole and would extend circumferentially around the chamber. In order to reduce this gap during winding, the MSFC team used manual techniques to guide the fibers while still under tension to close the gap as much as possible all the way around the chamber. Two triangular gap shapes were used around the port to reduce the discontinuity around the entire chamber. This helped for the wrinkling as more of the prepreg is covered by the hoop so there is less exposed area. In Figure 9 E, the back of the chamber was completely covered in hoop wrap and it was ready for the continued processing.



Figure 10 A. Shrink Tape



Figure 10 B. Custom Caul Sheet



Figure 10 C. Fiberglass High Tension Overwrap

Figure 10. Trial 3 Tooling

The team started with the shrink tape layer again, but added a layer of Teflon® tape for a resin leakage barrier. Two triangular rubber insets were made to fit into the spaces between the hoop layers left open to the prepreg. A custom caul sheet made of IM7/8552 was then also made to fit the exact area the prepreg covers on the chamber. This was placed directly on top of the rubber inserts and shrink tape. To provide significant pressure to the caul plate and rubber inserts, another layer of cheaper fiber was dry wound overtop at 8 lb_f of tension. The final product had significant improvement compared to the previous trials and reduced prepreg wrinkling and improved resin consolidation as shown in Figure 11.



Figure 11. Trial 3 Final Part Post Cure

4.2 Manufacturing Process Development at Kord

The chamber was transferred back to Kord to repeat the process developed at MSFC. Given the new direction from NASA, Kord had some goals for the continued winding process development:

Develop methodology to use Faro® laser 3D scanner to evaluate overwrap thickness.

Figure 13 shows the tooling that was used for the 40k hot-fire test article set up. A flange adapter was bolted to the forward end of the chamber and held in place on the shaft by a collar. A PTFE bell adapter plate was inserted in the aft-end bell to provide support for the nozzle to center around the shaft without flexing during winding.



Figure 13 A. Bolted Flange



Figure 13 B. RTFE Adapter



Figure 13 C. Chamber Prep

Figure 13. Filament Winding Tooling for 40k

Originally, the surface of the copper chamber was dark due to oxidation, so surf prep was needed before the winding procedure. Surface prep followed the same steps as the 7k chamber [3]. The remainder of the article that did not require winding was wrapped with high temperature Teflon® tape and bagged with vacuum bagging material and tack tape to protect from resin run off.

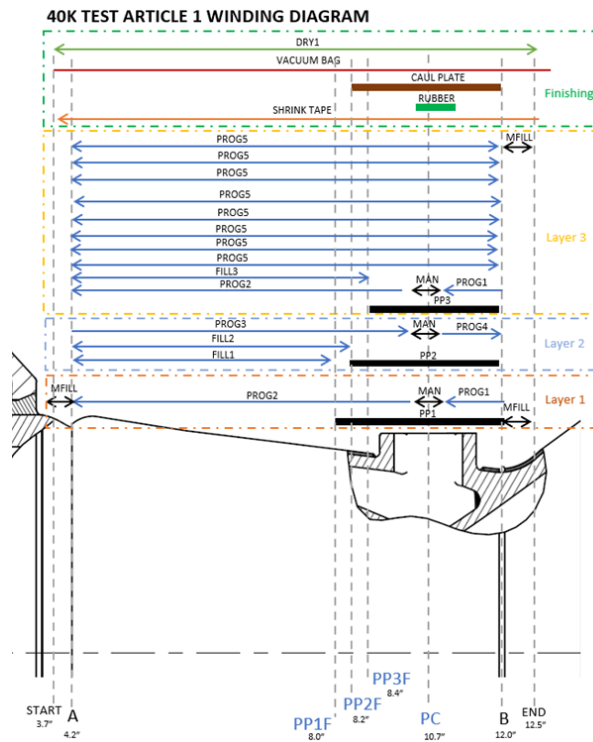


Figure 14. 40k Chamber Test Article Layup Diagram

Building on experience from all the previous trials, the winding diagram in Figure 14 was chosen for the test article. The final article's surface profile was slightly different from those of the manufacturing demonstration articles, which helped simplify the final layup. The wind was also conducted without cutting the layers between hoop layers. The visualization of the prepreg and hoop layer additions can be seen in the MSFC trial and Figure 15 shows the final layer of the test article before tooling and cure.



Figure 15. Test Article Before Cure

To prepare the article for cure the following steps were taken:

1. Applied shrink tape to the entire chamber section starting on the aft end and traversing to the forward end.
2. Applied the silicone rubber inserts and the NASA provided caul plate around the chamber port.
3. Covered the chamber region with high temperature vacuum bagging material and sealed the chamber port with bagging material and tacky tape.
4. Inserted the taped half inch strip of stick along the length of the chamber to be used as the cutting surface when removing the dry fiber.
5. Wrapped the chamber region with dry fiber with high tension.



Figure 16 A. Shrink Tape



Figure 16 B. Custom Caul Plate



Figure 16 C. High Tension Dry Overwrap

Figure 16. Test Article Tooling

Unfortunately, during the port seal operation, it was discovered that a buildup of material on the forward edge of the port had slipped under the fiber guide plug and covered a portion of the port lip. The issue was fixed to avoid a rewrap by cutting and bending a copper shim to hold back the fiber build up.

4.3 Test Chamber Lessons Learned

The overwrap was too thick with all the extra layers and caused significant build up around the port leading to the overwrap being higher than the actual port. The cap on the port concealed the edge so the overage was not noticed until the cap was removed. The inlet port attaches to a threaded

flange for the final test chamber so a couple extra layers will be removed in future builds. The extra build up caused a small change in the tooling design where a shim was added between the port hole and the overwrap to open up the flat surface of the port hole again. This also changed where the sealing tacky tape was added before cure. The change in tooling design also caused resin to infiltrate inside of the port into the individual chamber cooling channels. The resin leaking into the port causes a significant risk to the test article due to the potential to block the internal cooling channels. The chamber did have uniform surface finish and good resin consolidation all around. There was also no wrinkling in the prepreg area around the port.

5. CONCLUSION

The RAMPT project team has designed and successfully manufactured a series of additively manufactured (AM) GRCo copper-alloy combustion chambers with a composite overwrap to push the boundaries of current engine designs. Significant progress on the designs up to 40k-lbf thrust chambers contributed to good progress of the combined AM-composite technology during 2021 and 2022. Despite the chamber being considerably more difficult to wrap, the team was able to reach a final layup and tooling configuration that meet the given requirements. A future hot-fire test article will require minor changes such as adding a better seal to the port with a threaded attachment and modifying the wind program to prevent fiber build up around the port. The complexity of AM allows for niche design features such as the ridges/humps that were successful starting with the 2k chambers and continued for the larger chambers. With the successful build and demonstration of the 2k, 7k, and 40k chambers, the building block approach for RAMPT has been proven and the lessons learned can be applied to even larger sized thrust chambers. There have been successful tests of 2k and 7k chambers and the team anticipates the future testing of the 40k in 2023. This new hardware design and manufacturing approach can help the aerospace industry grow in creating more complex designs that lead to significant weight reduction, sustainable lower cost, and lead time reduction for flight hardware.

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