Fabrication of Composite Combustion Chamber/Nozzle For Fastrac Engine

T. Lawrence, R. Beshears, S. Burlingame, W. Peters, M. Prince, M. Suits, S. Tillery, Marshall Space Flight Center, L. Burns, M. Kovach, K. Roberts, Thiokol Propulsion Group

Abstract

The Fastrac Engine developed by the Marshall Space Flight Center for the X-34 vehicle began as a low cost engine development program for a small booster system. One of the key components to reducing the engine cost was the development of an inexpensive combustion chamber/nozzle. Fabrication of a regeneratively cooled thrust chamber and nozzle was considered too expensive and time consuming. In looking for an alternate design concept, the Space Shuttle's Reusable Solid Rocket Motor Project provided an extensive background with ablative composite materials in a combustion environment. An integral combustion chamber/nozzle was designed and fabricated with a silica/phenolic ablative liner and a carbon/epoxy structural overwrap. This paper describes the fabrication process and developmental hurdles overcome for the Fastrac engine one-piece composite combustion chamber/nozzle.

Introduction

The Fastrac 60,000 pound thrust engine (60K) combustion chamber/nozzle, referred to henceforth as the nozzle, began as part of a low cost technology demonstration effort. Development began at the 15 thousand pound thrust (15K) size with material performance testing and was scaled up to the 40 thousand pound thrust (40K) "flight" type demonstration size. The final 60K design has the same inner contour as the 40K with changes driven by process development and X-34 flight requirements. The technology efforts were combined into a low cost engine design under NASA's Low Cost Booster Technology project to demonstrate that a robust, low cost engine was an attainable goal.

As part of the Low Cost Booster Technology project, the engine was designed for use in an expendable booster. This significantly impacted the material selection and engine packaging. A composite liner and structural overwrap with bonded metal attach hardware were selected for development. In comparison to a regeneratively cooled thrust chamber assembly, composites were an order of magnitude cheaper and could be produced in less than one-sixth the time. With a composite design the combustion chamber and nozzle could be fabricated in a single unit, removing the complexity and weight of a joint design. The composite design also reduced the complexity of the engine since no fuel would be pumped through the component walls for cooling.

Silica/phenolic was selected as the ablative liner material and carbon/epoxy was selected as the structural overwrap. The silica/phenolic material selection was made based on knowledge and experience gained from the Space Shuttle's Reuseable Solid Rocket Motor (RSRM) and the Solid Propulsion Integrity Program. The composite processing knowledge and automated processing capabilities at the Marshall Space Flight Center (MSFC) provided the foundation to combine the materials into a single unit and to achieve the goal of low cost.

When the engine was switched from the expendable booster to the reusable X-34 the biggest problem was the packaging. Nozzle changeout was not considered a critical issue with the expendable design so easy changeout was not incorporated. The turbopump, gas generator, and thrust vector attachment were all packaged to attach to the nozzle. Had the original purpose been a reusable design all of these would have been packaged on the powerhead so the nozzle could be easily replaced.

The remainder of the paper will describe processing of the liner, overwrap, and bonding. Included will be the lessons learned in each section. The majority of the lessons learned came after the failure of 60K-01, which will be described in greater detail in the liner processing section. Nothing can replace learning by doing and this project, having been worked from initial concept to hot fire testing, has provided a tremendous learning opportunity for all those involved.

The Liner Process

The purpose of the liner is to form the flame side contour and to protect the structural overwrap and bondlines from excessive temperatures. For the 60K engine to meet its performance goal, erosion had to be almost zero. To minimize erosion, a small percentage of fuel is sprayed down the chamber wall to provide a layer of film coolant. The film coolant also helps to prevent hot spots and streaking in the chamber. Testing to date has shown no measurable erosion with an accumulated test time of up to 342 seconds. Flight requirements call for the engine to fire for 159 seconds.

Liner processing is the first step in fabrication of the Fastrac nozzle. Silica/phenolic bias tape, FM5504, is tapewrapped onto a steel mandrel using a horizontal tapewrap machine. The ply angle, the angle of the tape to the flame surface of the liner, directly affects erosion performance and stress levels of the part. Based on thermal-structural analysis, this ply angle had to be changed twice, once in the throat and once just aft of the throat (see Figures 1 & 2). This was accomplished by tapewrapping past the ply angle change and then machining a new ramp angle in the uncured silica/phenolic. Computed tomography X-ray (CT) of the overwrapped part and posttest sectioning demonstrate a well-consolidated part at the ply angle change.

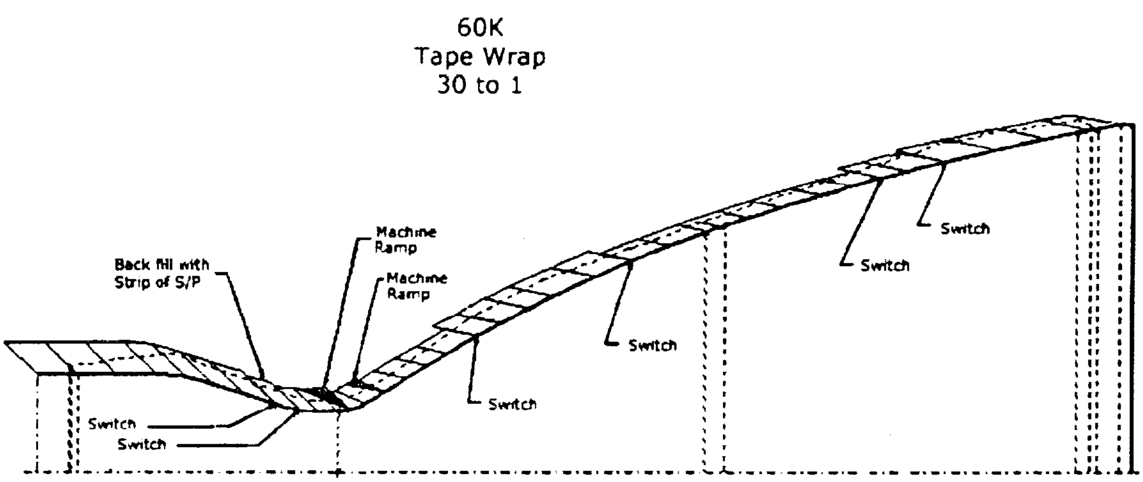

Figure1. Tapewrap Process Drawing

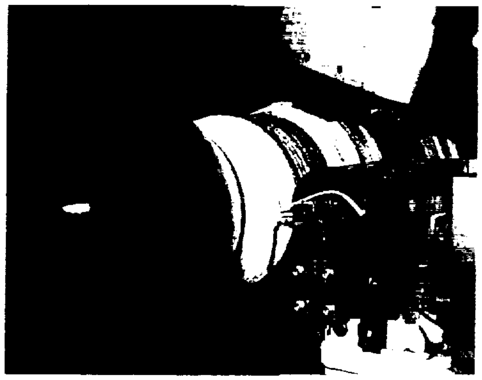

Figure 2. Machining of new ramp in uncured Si-P liner

Once the tapewrapping is complete the part is vacuum bagged and cured in an autoclave. Because of the complex shape of the nozzle and the sensitivity of silica/phenolic to cracking during cure, development of an appropriate cure cycle was critical. The cure cycle was established using data generated from instrumented panels of similar thickness and the cure model developed by the RSRM project.

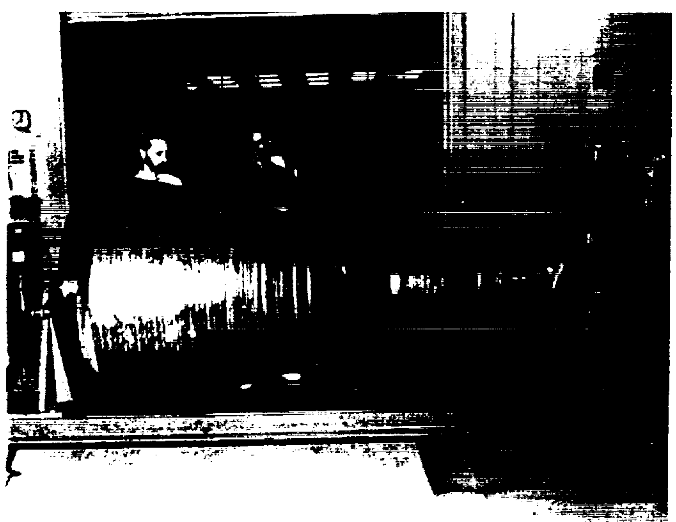

Figure 3. Cured Si-P liner billet

After liner cure the forward tag end is machined and the liner is removed from the mandrel. The liner is returned to the machine shop to have the outer diameter contoured in preparation for the overwrap process. The machined surfaces are inspected for wet line indications by alcohol wipe and then sent to the overwrap step.

Lessons Learned

As a result of lessons learned, several minor changes were made to the fabrication process and one significant change was made to the silica/phenolic tape to improve the quality of the liner. One minor change involved modification of the machining process used to cut the new ply angles in the uncured silica/phenolic. The first ply angle ramps were machined roughly and produced resin pockets visible in the post-cured computed tomography images. Once the ply angle ramp machining was improved to provide a smoother ramp, the resin pockets were essentially eliminated. Another process change was made because the 60K-03 and 04 nozzles had very poor consolidation and flow in the throat region. This problem in the throat developed because the o-ring in the throat centerline joint of the mandrel was improperly sized and leaking. Rather than reworking the mandrel, the planning was changed so that the joint was filled with room temperature vulcanized silicone rubber (RTV) during mandrel assembly. The problem has not recurred.

During the investigation of the problem with the mandrel leakage it was determined that the part was too large for only an aft tag end. The mandrel was modified to increase the chamber length sufficiently for a forward tag end. The forward tag end is removed after liner cure and prior to the overwrap process. The data from the tag ends is charted and evaluated for any trends indicating a shift in the process or in the properties of the liner or overwrap materials.

Early in the nozzle development process, most of the cured components had dry regions because the material was overstaged during tapewrap. There were regions where the plies were rolled over on the inside surface because of significant tape to mandrel gaps. The operators performing the tapewrapping were asked to look at the cured component and once they saw how the final part looked and how their work could affect the part, significant improvement was made in the part quality.

The last minor change to be discussed involved the silica/phenolic specification for resin flow. One lot of material received had a resin flow that was on the low end of the specification. This material produced an acceptable part but was much harder to tapewrap and the resin did not flow as well during cure. The cured part resin content exceeded the upper specification limit and additional testing had to be performed. To keep the cured part within resin content specifications, the lower flow limit for the silica/phenolic was raised on subsequent material orders.

The most significant change to the liner began with the failure of nozzle 60K-01 during ignition on its third hot fire test. Prior to the third test, scheduled to be 120 seconds, 60K-01 had undergone a 20-second and 12 second test. Although the nozzle was designed for a single use, testing during the 40K test series had demonstrated that multiple short duration tests could be run on a nozzle without jeopardizing its survivability. At ignition the liner failed approximately 2 inches aft of the throat region. Since the performance of the combustion chamber was not affected, the test was continued for 59 seconds to gain needed injector performance data. The exposed structural overwrap burned, destroying data that would have been useful to the failure investigation team. Review of the high-speed video and reassembled liner pieces showed the exit cone portion of the nozzle was ejected as a single piece at ignition. The liner broke into pieces as it struck the ground and was then tumbled across the test pad by the engine exhaust plume.

The cause of the failure was determined to be a delamination that extended through the entire thickness of the liner, combined with a poor liner to overwrap bondline from the delamination point aft. Posttest CT found an axial crack in the liner which ran through the chamber and throat and ended at the delamination in the exit cone (see Figure 4). With the liner continuity broken there was nothing holding it in place. The poor bondline was caused by the inadvertent omission of a dry cycle, which is discussed in the overwrap section.

The primary cause of the liner failure turned out to be a supposedly transparent material change in the silica/phenolic. For the 40K program FM5504 silica/phenolic was used. Between the time that the 40K material was purchased and the time the material was purchased for the 60K program, Fiberite bought the producer of FM5504 and decided to phase it out and manufacture only their version of the same product, MX2600. Since both materials had been qualified for use on the RSRM and met the same specification, it was believed they would behave in a similar manner. The material change was made with no preliminary testing; a test matrix was to be performed concurrently with the fabrication and hot fire testing of the 60K components.

To evaluate the material differences, cylinders with a diameter the size of the 60K throat were made of the two materials and hoop tensile tests run at Southern Research Institute. The results, shown in Figure 5, clearly show the problem with the MX 2600. With reduced strain capability the MX 2600 could not survive the stresses put into the liner during overwrap cure. This was demonstrated when several liners made with MX 2600 and possessing good bondlines cracked axially in the chamber and throat down through the nozzle until they were stopped by a 360 degree liner delamination. With this information Fiberite agreed to supply the FM5504 and no problems have been encountered with the liners cracking.

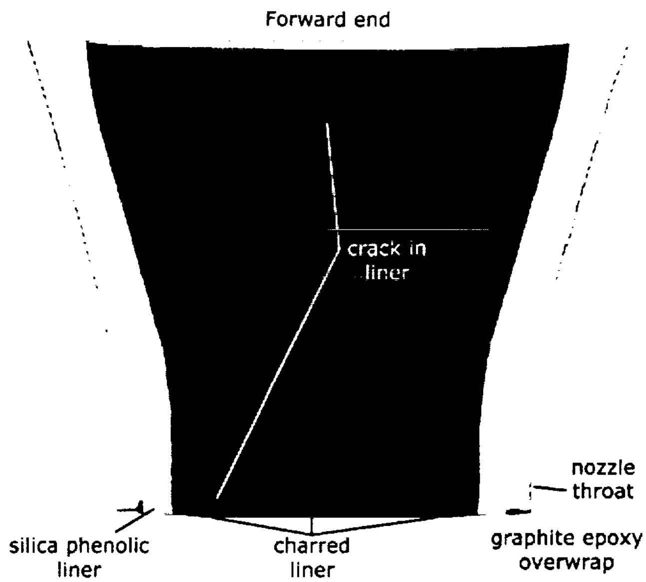

Figure 4. CT Image of Axial Crack in 60K-01 Chamber and Throat

The old FM 5504 data listed on the plot is material from the 40K development series (old) made at the original manufacturer's facility. The new FM5504 data is from material made at the Fiberite facility (new) after the original manufacturer was purchased. With the return to FM 5504, no liners have cracked in the chamber and throat regions in a total of 40 units built. The old lesson relearned many times in this industry was again demonstrated; though materials may meet the same specification, that does not guarantee that they will perform the same. The selected material must be well understood and no change should be viewed as insignificant.

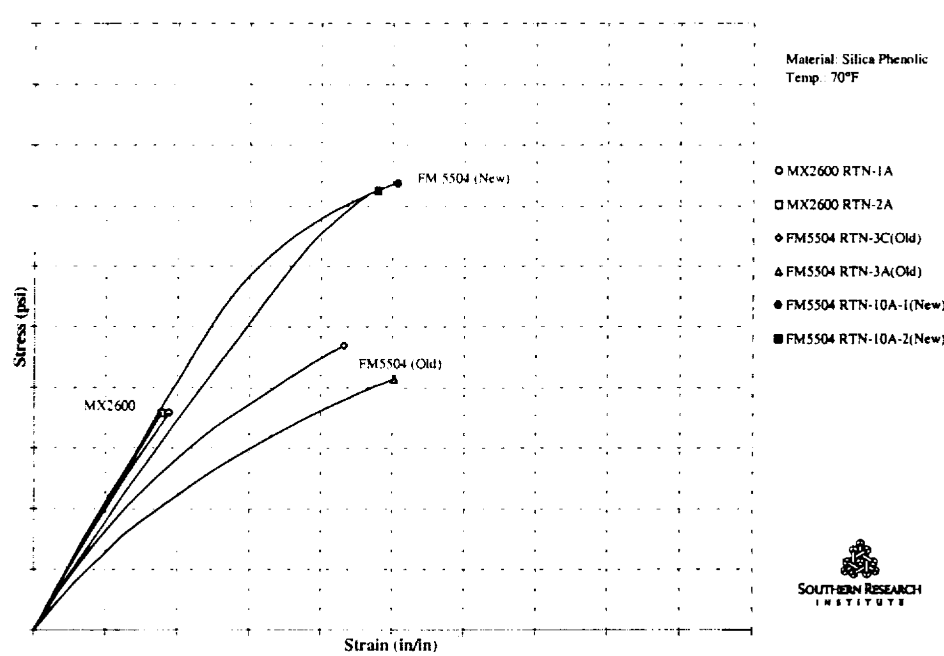

Figure 5. Ring Tensile Data for FM5504 vs. MX2600

The Overwrap Process

The purpose of the overwrap is to provide structural support to the silica/phenolic liner. The materials and processes were originally selected based on low-cost and minimized part count. Much of the process development work was done during the investigation of the 60K01 failure. The standard overwrap material is carbon/epoxy although several nozzles were overwrapped with fiberglass/epoxy. The fiberglass/epoxy was chosen as a result of the failure investigation with the intent of more closely matching the thermal expansion of the liner and overwrap materials.

The first step of the overwrap process is the liner dry cycle. The liner is subjected to high temperature to drive the moisture from the machined silica/phenolic surface. Moisture can negatively impact the bondline between the silica/phenolic and the carbon/epoxy. The temperature of the silica/phenolic must be ramped slowly to avoid potential cracking.

After the dry cycle, the liner is mounted onto the filament winding mandrel and the stainless steel flange is mated to the combustion chamber portion of the liner using Hysol® EA 9628 film adhesive. Film adhesive is applied to the entire liner surface and carbon/epoxy is then wet wound over the film adhesive (Figure 6). Thornel® T-300–12K carbon fiber and Epon® 828 resin were chosen because of their low-cost and commercial availability. Epi-Cure® W curing agent was chosen because it has an extended pot life which accommodates the time required for winding and curing of such a large part.

Figure 6: Wet winding of carbon/epoxy over silica/phenolic liner covered with film adhesive.

The overwrap is vacuum-bag-oven-cured with a temperature cycle that, like the dry cycle, involves a slow ramp rate to avoid cracking of the silica/phenolic. After cure, the ends of the nozzle are cut off using a grinding wheel mounted to the vertical carriage of the filament winding machine. The mandrel is then removed and the nozzle is machined in preparation for bonding of the metal hardware.

Lessons Learned

During the development of the overwrap process several challenges were overcome. Many were a result of work done during the investigation of the 60K-01 failure. Some of the most notable challenges were wrinkling of the overwrap in the throat region after cure, bridging of the fibers in the transition regions, crack initiation in the nozzle at the very aft end and mandrel expansion during cure.

The overwrap mandrel is a "Christmas Tree" design that supports the liner in the combustion chamber area and two places in the nozzle region (Figure 7). The forward end is attached by the combustion chamber flange to a dome/pin ring. The dome/pin ring is held in place by a large nut with a spring washer. The spring washer serves to apply pressure to the flange and keep it properly seated on the combustion chamber portion of the liner as the mandrel expands during cure. During the development of the overwrap process, slippage between the mandrel and the inner liner surface was suspected. Nitrile butadiene rubber (NBR) was placed on the aluminum mandrel rings to prevent slippage.

The NBR also serves another purpose. The liner at the aft end tapered down to a fine edge that was easily chipped. The chipped area allowed cracks to initiate and propagate into the aft end of the liner. The potential for crack propagation was exacerbated by the wedge effect of the mandrel. The wedge effect is caused by the expansion of the liner during cure with the spring washer forcing the liner onto the mandrel rings. The mandrel rings act as a wedge that tries to open the nozzle portion of the liner. This problem was solved by machining the aft end of the liner to a flat edge before the overwrap process to prevent crack initiation. Application of the NBR to the mandrel rings also helped alleviate the potential for cracking by isolating the rings from the liner surface to allow relative movement during expansion and contraction.

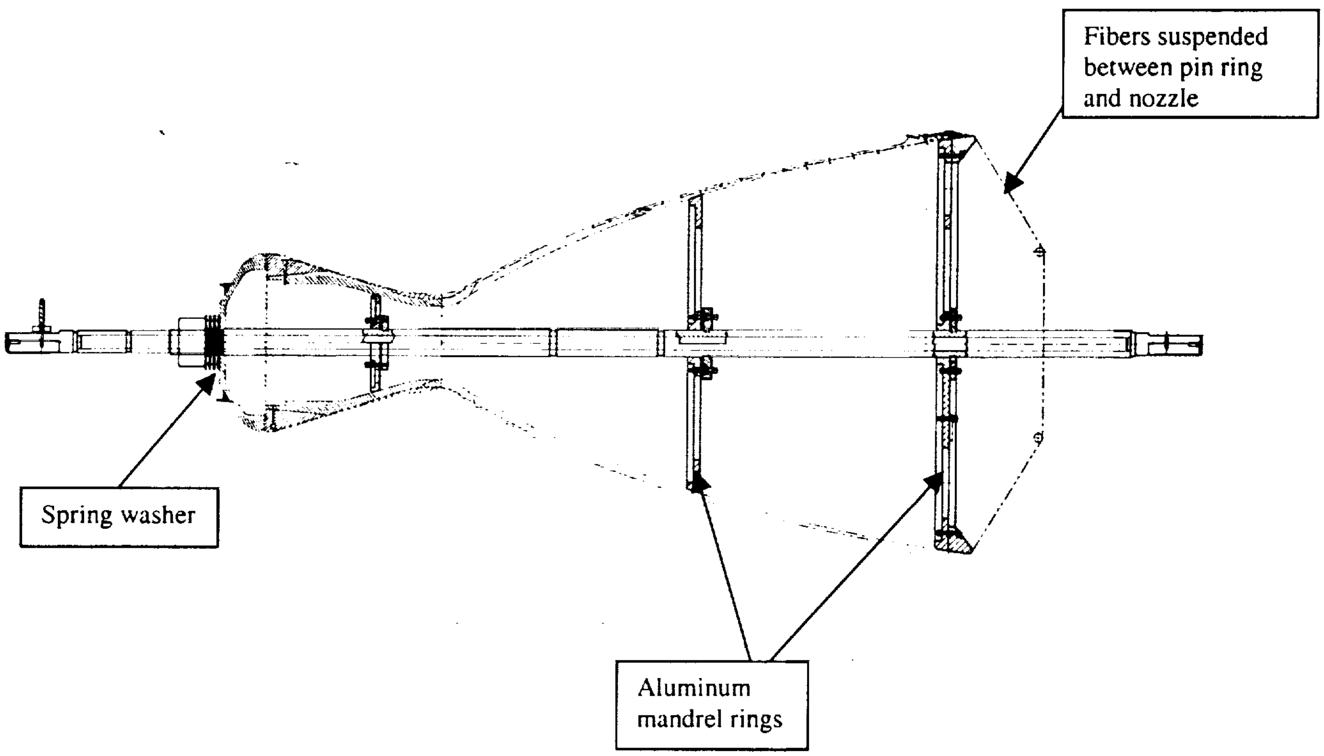

Figure 7: The filament winding mandrel is a "Christmas Tree" design. A spring washer between the forward dome and the lock nut keep the flange properly seated during cure.

Another issue that was overcome was wrinkling of the overwrap in the throat region. The bagging technique was adjusted to trap resin in the composite. This was accomplished by switching from perforated to non-perforated release film. The non-perforated release film was selectively punctured in and around the throat region to allow volatiles to escape but minimize the amount of resin lost. After several iterations the wrinkling was eliminated. This process also accomplished the task of increasing the diameter of the throat.

The throat area is machined for the application of the belly band hardware so a larger throat diameter assured that enough composite would be present for machining.

After the failure of 60K-01, the residual stress in the bondline between the overwrap and the liner became an important issue. One of the reasons for the residual stress in the bondline was the tooling and vacuum bag configuration. At the aft end, the wound fibers and vacuum bag are suspended between the pin ring and the end of the nozzle. The vacuum forces this suspended area down and increases fiber tension (see Figure 7). To minimize the impact of this effect, the first wound layer is cut flush with the aft end of the nozzle. This relieves the tension in the first layer of fibers and therefore reduces the amount of residual stress created during cure between the overwrap and the liner. Relieving the tension in the first layer also serves to reduce the potential for bridging of the wound fiber over the transition from the throat to the nozzle and the bump in the liner for the actuator attachment ring.

NonDestructive Evaluation

Once the overwrap is machined and prior to bonding on the metal attachment hardware, the nozzle is inspected by CT and ultrasonic spectroscopy (Ultraspec). These are two state of the art nondestructive evaluation (NDE) techniques that give excellent insight into the consistency of the process and the resulting part. The CT inspection looks for cracks, delaminations, and density gradients in the component which are unacceptable or out of family. The Ultraspec inspection is a technique developed by Southern Research Institute that detects debonds between the liner and the overwrap. Kissing debonds cannot be detected by CT but the Ultraspec can detect them. The Ultraspec was added to the program during the 60K-01 failure investigation. Several papers could be written on what has been learned through the use of these tools and it will be left to the appropriate experts to perform that task. Let it suffice to say that these advanced techniques have been instrumental in the success of this project.

The Bonding Process

After the overwrap is machined and NDE is performed, additional metal and composite hardware are physically bonded to the nozzle. This additional hardware facilitates attachment of the nozzle to the injector and the Thrust Vector Actuation (TVA) system. This hardware also provides mechanical support for components such as the gas generator/turbopump, igniter, exhaust duct, valve brackets, and drain lines. Figure 8 shows a nozzle with all hardware bonded and the Thermal Protection System (TPS) applied and painted.

Figure 8: A photograph of a completed nozzle with all the hardware bonded (arrows) and the TPS applied and painted (white region).

The first three components bonded to the nozzle are the gas generator/turbopump/igniter support belly band, the actuator attachment ring (AAR), and the exhaust duct support bracket. These components are machined from 300 series stainless steel. The remaining components, the valve bracket and drain line support pads, are molded from a composite sheet molding compound (SMC), Lytex™ 9063, manufactured by Quantum Composites Inc.

All of the bonding operations are performed in much the same manner. The hardware is placed in a fixture or tooling is put in place to insure accurate positioning. The hardware is then dry fitted to the nozzle to verify positioning and to determine shimming requirements. The shims aid in placement of the hardware during actual bonding and also provide a minimum bondline thickness for the adhesive. The next step is surface preparation. The exact surface preparation method is dependent on the material of the surface being bonded. Metal hardware is hand wipe cleaned, grit blasted with a zirconia or silica media, inspected by black light, and then primed with a silane-based primer. Composite hardware, and the surface of the chamber/nozzle itself, are hand wipe cleaned and grit blasted with an alumina media. Shims are then affixed to the hardware as required, and surfaces of the nozzle and hardware that are not involved in the bonding operation are masked. The adhesive used for bonding operations on the Fastrac engine is Hysol® EA 9394, a two part structural paste adhesive. The adhesive is mixed and then applied to both the hardware and the nozzle surface. Following adhesive application the hardware is positioned and held in place until a sufficient degree of cure is achieved to allow nozzle movement.

Two components, the AAR and the exhaust duct support bracket, undergo additional processing to install shear bolts following initial bonding. The shear bolts enhance the transfer of loads from the AAR and exhaust duct support bracket to the nozzle. The bolts ensure that the loads are transmitted to the entire thickness of the nozzle and not just the outer ply of the structural overwrap. Holes are machined through the metal hardware and the structural overwrap and into the silica/phenolic liner. The bolts are then installed wet with Hysol® EA 9394 adhesive and the adhesive is allowed to cure.

The TPS consists of sheet cork bonded to the exterior of the overwrap with Hysol® EA 9394 adhesive. The process is performed using standard vacuum bagging techniques. An ablative compound, RT-455 from Resin Technology Group LLC, is then applied to cover the exhaust duct support bracket and to fill in any gaps in the cork. Following cure, the cork and RT-455 are coated with an acrylic latex paint produced by Acrymax Technologies, Inc., SP130XT-LV.

Lessons Learned

Most of the challenges encountered in the evolution of the bonding process related to development of tooling and techniques to insure correct positioning of the hardware. Of necessity the initial tooling was makeshift and prone to errors and excessive variability. Over time it has matured into a very stout and reliable production system. This system includes a specialized fixture and tooling plates used to hold the metal components and the entire nozzle in place during bonding (Figures 9 and 10). Optical alignment equipment was used to set up the fixture. This assured proper leveling and parallelism. Axial adjustments are made to the components being bonded using two-piece tooling plates mounted to a drive screw system. In addition, a plumb bomb was incorporated into the fixture to aid in angular positioning of the hardware. To maximize positional accuracy, all measurements are taken relative to the combustion chamber flange and each of the bonding operations is performed independently. Lastly, hardware locations are verified following bonding using a portable coordinate measuring machine (CMM).

During process development the bonding plates underwent significant refinement. The bonding plates for the belly band were modified to more closely match the taper of the nozzle. This allowed for a better mating with the nozzle and sufficient room for the belly band plates to actuate more effectively. In addition, the thickness of the exhaust duct support bracket bonding plates was increased to eliminate unwanted flexing. The reasons for the flexing were twofold. First, the exhaust duct support bracket is mounted at the largest diameter portion of the nozzle, so the width of its bonding plates is the smallest of all the plates. Second, during bonding the adhesive provides a resistance to placement of the hardware in the form of a hydraulic pressure. Flexing also occurred with the positioning plates that support each belly band half and actuates them toward the surface of the throat. As the plates were extended toward the throat, the weight of the belly band halves caused flexing. Separate actuating supports were installed to allow the positioning plates to be supported along their full range of motion.

Tooling was also the key to sufficient accuracy and precision when bonding the composite/SMC components. The composite/SMC components are bonded to the nozzle in sets of 2-3 pieces each, using tooling that bolts to the previously used bonding plates or the previously bonded hardware. This tooling was developed based on models of the hardware to be attached to the nozzle during final assembly. Figure 11 shows the bonding of the valve bracket support pads to the nozzle.

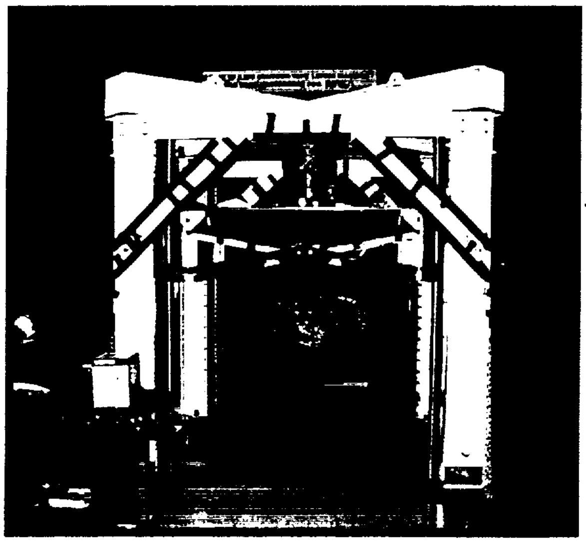

Figure 9: (left) *A photograph of a nozzle in the fixture with the belly band being bonded.*

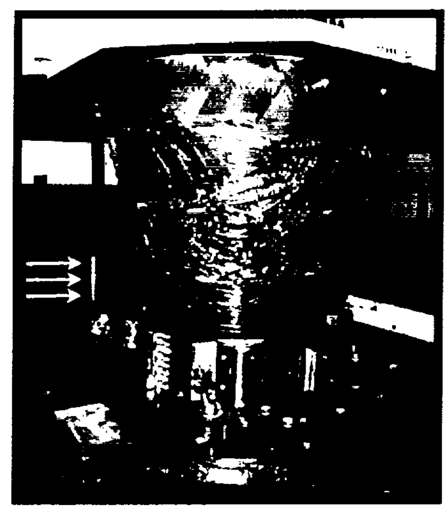

Figure 10: (right) *A close-up of the specialized tooling plate being used to bond the belly band. The arrows point to the plumb bob used to ensure angular position.*

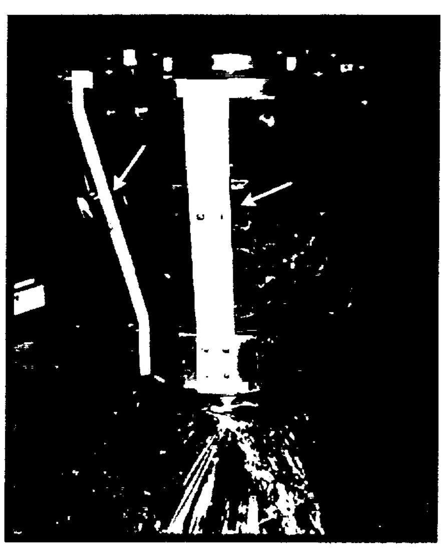

Figure 11: (left) *A photograph of the tooling used to bond the valve bracket support pads (arrows). This tooling fastens to the combustion chamber flange and the belly band to correctly position the pads.*

Summary

The development of a low cost nozzle for the 60K Fastrac Engine has been successful. The success was achieved by using well-understood material technology in a new way. Ablative, bonding and TPS technology from RSRM and structural composite technology from multiple projects provided the knowledge. With a little innovation and willingness to take some risk these materials were combined into a single unit with no joints. The manufacturing was simple, it contained a minimum number of steps and as much automation as possible. The only exception being the TPS that used old, hands-on technology due to project cost constraints at the decision point.

A significant amount of testing has been performed to evaluate the nozzle's capability to successfully meet the X-34 flight requirements. Flight requirements are for each nozzle to be used for a single, 159-second burn, and to survive intact the reentry and landing loads. To date, a shortened development nozzle has survived 4 starts and an accumulated 342 seconds of hot fire and a full-length development nozzle has survived 7 starts and an accumulated 282 seconds. In order to evaluate the capability of the bonded actuator attach ring, one nozzle actuator attach ring was loads tested and failed at 180% of the maximum expected load. The nozzle design was modified based on thermal–structural analysis and testing continues to verify the nozzle satisfies all performance requirements. Nothing has been found that would indicate future problems. The nozzle is believed to have demonstrated that it is a robust, low cost design for liquid engine applications and similar designs could be incorporated into other systems.

Acknowledgments

The success of this project is due to the many people at all levels who have taken a special pride in creating a robust component. A special thanks goes to the many technicians at Thiokol, Lockheed Martin, and ASRI whose craftsmanship and commitment were instrumental in resolving the issues faced during the development of the nozzle.