120MM PRESTRESSED CARBON FIBER / THERMOPLASTIC OVERWRAPPED GUN TUBES

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ABSTRACT

Advanced composite materials are need for lightweight large calibre weapons systems. The use of a thermoplastic resin, with fibre placement under tension has overcome the traditional problems of the coefficient of thermal expansion mismatch between the substrate and the jacket, and the lack of favourable prestress in the jacket. Three 120mm gun tubes were designed, built and tested using this process. The second barrel was the first composite tube to undergo fatigue testing after test firing

1. INTRODUCTION

Previous composite wrapped gun tube efforts have been undertaken by Benét Laboratories during the late 1980's and early 1990's. These efforts led to the fabrication and test of several 105mm and 120mm gun tubes. The coefficient of thermal expansion (CTE) mismatch between steel and composite caused a gap, on the order of 0.1 mm (0.004 in), between the composite overwrap and the steel, which effectively prevented or reduced the load carrying capability of the composite. To close the gap, the gun tube was autofrettaged (method of achieving compressive residual stresses at the bore by plastic deformation) after the application of the composite. The autofrettage closed the gap, and imparted some favourable residual stresses to the gun tube structure. There were, however, three problems with this approach; first, the thermal soak treatment used to stabilize the residual stresses in the tube after autofrettage could not be conducted as it is done at temperatures of 343 to 371 °C (650 to 700 °F) which is well above the maximum use temperature of the composite. The second was that the tube could not be chrome plated since the process requires the tube to be immersed in chromic acid, which would destroy the composite and contaminate the plating bath. The third problem is the creation of extremely high radial stresses at the steel / composite overwrap which may be higher than firing stresses (Parker et al., 2005).

One approach to solving these problems was the 105mm Multi-Role Armament and Ammunition System (MRAAS) Swing Chamber Launcher (Littlefield and Hyland, 2002). In this case the CTE mismatch was handled by tailoring the lay-up. A combination of fiberglass and graphite was used with the ply angles being adjusted such that the lay-up's CTE matched that of the steel. This resulted in no gap forming between the composite and the steel but the performance of the composite was not optimum.

The composites used on these efforts were all thermoset materials; therefore they required curing. For the current Advanced Technology Demonstration (ATD) effort, thermoplastic composites are being used. The advantage of thermoplastics is that they do not need a cure cycle but can rather be melted and recrystalized / consolidated immediately after being placed on the gun tube. This results in a "cure in place" type fabrication technique. Heating of the composite is localized, minimizing heat input to the composite and gun tube. This process mitigates thermal expansion effects and effectively eliminates the gap problem. The composite can therefore be placed onto the gun tube after the autofrettage thermal soak and chrome plate application.

Firing data have shown that the measured strains are typically higher than expected from static ballistic pressure alone. This increase in tube strain is attributed to both the loading condition, which is effectively a square wave, as well as high speed dynamic loading of the gun tube during projectile passage. In most cases, this strain is typically 8-10% above the statically predicted (open ended cylinder, Lame equations) values. In situations where thin walled gun tubes and high velocity projectiles are used, the strains can be significantly higher, on the order of 300-400%. This phenomenon is known as gun tube dynamic strain and has been an area of study for many years by Benét Laboratories (Hasenbein et al., 1990; Hasenbein and Hyland, 1992; Simkins, 1987). In the development of the Light Weight 120mm (LW120) cannon, this phenomenon will be of special interest since the LW120 will have a thinner tube wall than the current 120mm M256 cannon and thus it will be more prevalent.

The 120mm Line of Sight / Beyond Line of Sight (LOS/BLOS) ATD is tasked to design, develop & demonstrate new armament & ammunition technologies for use in the Army's Future Combat System (FCS). The specific role the ATD plays is to support the development of the main armament for the Mounted Combat System (MCS), which will be equipped with a 120mm main armament and will provide Line of Sight and Beyond Line of Sight firing capabilities.

The focus of this report is the use of an organic composite overwrap to lighten the weight and reduce the imbalance of the gun tube. The first tube, Serial No.

ATD-1, was the first large caliber gun tube to be wrapped with thermoplastics and was reported on previously (Littlefield et al., 2006). This report will focus on the three follow on composite wrapped tubes: ATD-3, ATD-5 and ATD-6. These tubes use the same materials as ATD-1 but they have very different lay-ups and were the first gun tubes to be wrapped under tension.

2. DESIGN AND ANALYSIS

Initially a lightweight all steel 120mm gun tube was designed using traditional methods. This design had a weight of 889 kg and length of 5460 mm. The composite design was to match or exceed the frequency of the first bending mode of the steel design and match the residual hoop stress distribution through the tube wall, while saving weight.

IM7 fiber with a polyetheretherketone (PEEK) matrix was the material selected for this project for several reasons. The first is the superior strength (2.07 GPa (300 ksi) in the fiber direction), modulus (138 GPa (20 msi) in the fiber direction) and toughness of the composite when compared to the majority of thermoset and other thermoplastic materials. The second reason for the selection of this material was its high melt point (653 °F / 345 °C). The final reason for the selection of this material was its excellent chemical resistance; in particular, its resistance to petrochemical fluids that would be encountered in the day to day operation of a large machine. The cost of thermoplastics, while in general higher than thermoset counterparts (~20%), was offset by the fact that there would be no autoclave post cure required.

The tubes natural frequency (especially the first bending mode) affects the gun aiming and stabilization system. Maintaining the same natural frequency as the current gun tube minimizes changes to these systems. In addition, if the tube natural frequency gets too low, it may approach the natural frequency of the riding loads of the vehicle. Excitation of the gun tubes natural frequency may then occur leading to a condition in which stabilization of the gun tube becomes impossible. Large caliber gun tubes often use autofrettage to impart favorable residual stresses into the gun tube structure. Since we were replacing some of the steel with composites, it was vital that the composite provide the same residual stress distribution as the original steel. To accomplish this, the residual stress distribution through the tube wall, including autofrettage and the composite wrap, were modeled.

Previous work at Benét Labs (Hasenbein et al., 1991) was employed to properly model the dynamic effects of a pressure wave moving down a gun tube and to ensure the correct high frequency data was captured. An axisymmetric FEA model was created using 8-node biquadratic axisymmetric quadrilateral reduced integration elements (CAX8R). Previous work on ATD-1 (Littlefield et al., 2006) showed that for this type of problem the jacket could be accurately modeled by attaching it with tie constraints and using smeared orthotropic properties.

Static, normal mode and dynamic analyses were all performed. For the dynamic analysis, a pressure load was moved down the bore of the tube to simulate a projectile. A graphical result of this analysis can be seen in Figure 1.

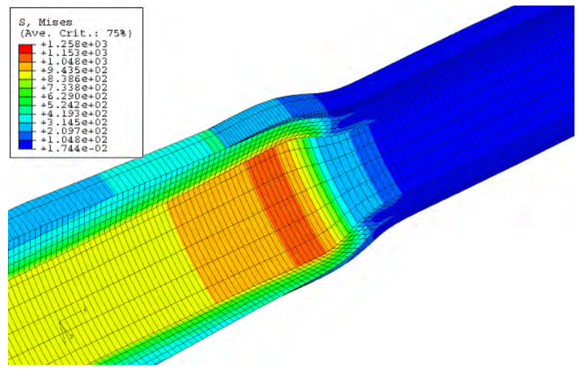

Figure 1–Dynamic FEA analysis of a steel tube with a composite jacket

These analyses were repeated until a lay-up was arrived at that met or exceeded all of the metrics. The final lay up consisted of 72 plies of IM7/PEEK with a mixture of hoop and axial plies. The hoop plies were wound under tension to match the residual stress distribution of the original all steel design. A cross ply layer of S2/PEEK was added to the outside to protect the carbon fiber layers. This lay-up resulted in 113.4 kg (250 lbs) of steel being removed and 20.4 kg (45 lbs) of composite being added for a net weight savings of 93 kg (205 lbs).

3. MANUFACTURE

The steel portion of the gun barrel was manufactured according to the normal process, except that an area was undercut for the composite.

The composite was applied utilizing a robotic fiber placement process to precisely place and consolidate strips of thermoplastic prepreg tape. The process uses a hot gas torch (HGT) to melt the prepreg and then consolidates it with a pressure roller. Throughout the process the tape is held under tension and upon cooling this tension is locked in; inducing a residual stress into the part.

There were three major issues that needed to be overcome in order to fabricate the overwind:

- Tightness of fit between overwrap and barrel
- Galvanic corrosion between overwrap and barrel
- Maintaining the desired outside diameter (OD)

Winding under tension helps to ensure a tight fit between the overwrap and barrel. Additionally, the barrel was cooled causing it to shrink during processing. Upon returning to room temperature the barrel attempts to grow in size but is constrained by the composite. This approach uses the CTE mismatch to ensure a tighter fit instead of causing a gap. This cooling process was found to induce level of residual stress equivalent to approximately 133 N (30 lbs) of winding tension.

Additionally the cooling helps to remove the heat generated from the fiber placement process. Without cooling the barrel temperature would have quickly heated to between 60 and 65 °C (140 to 150 °F). The exact temperature cannot be released but it was within the operational temperature of the gun system. The temperature was monitored at the coolant inlet, the breech, and muzzle. These three values were then used to control the amount of coolant introduced into the tube to maintain the desired substrate temperature.

If carbon fiber is brought into direct contact with steel, galvanic corrosion would take place. To avoid this, two layers of S2 fiberglass / PEEK were placed between the steel and the carbon fiber. This thin layer is enough to act as an insulator but thin enough to not effect the performance of the overwrap.

Due to some standard variation in raw material thickness (specification for the material allows a +/- 0.0127 mm variation in tape thickness), close attention was paid to the OD during fabrication. Modifications to ply lengths and locations were made to maintain the desired final OD.

Figure 2 shows an axial ply being applied to the gun barrel. The white area is frost that develops on the part due to the chilling of the barrel. The hot gas torch vaporizes this as it applies the tape, so that none of the moisture finds it way into the part.

Figure 2–An axial ply being applied to the gun barrel

This same basic process was used for all three tubes but there were some improvements made along the way. ATD-3 was fabricated by Automated Dynamics (ADC) while they were fabricating Benét's new fiber placement machine. ADC used 25 mm (1 in) wide tape during fabrication so the outer cross-ply layer was wrapped at +/- 75 degrees. Also the cooling was performed manually. After wrapping it was found that the ends of the cross-ply layer were prone to peeling. This was fixed by coating the ends in epoxy.

ATD-5 and ATD-6 were wrapped in house at Benét on the new fiber placement workcell. In this new system the tension and cooling were directly controlled by the machine with limited operator intervention. 12.5 mm (0.5 in) tape was used for wrapping these tubes so the cross-ply was done at +/- 45 degrees. To prevent the cross-ply peeling issue a 203 mm (8 in) +90 / -90 band was added to each end of the lay-up.

4. NON-DESTRUCTIVE EVALUATION

Modal impact testing was performed prior to applying the composite and after applying the composite to determine effect of the overwind on tube stiffness. Modal testing was also planned for after firing for all three tubes to look for any detrimental effects of the test firing, however other higher priority testing precluded this form being done on all tubes except ATD-3. In all cases the tube was hung from springs to simulate free-free boundary conditions. This setup can be seen in Figure 3.

Figure 3–ATD-6 Modal Testing Setup

Accelerometers were placed at the muzzle and every foot (304.8 mm) down the length of the composite. For ATD-3 and ATD-5, the tube was impacted 219 mm (8.625 in) from the muzzle with a modal impulse hammer and the response of the accelerometers was recorded. After this, all but the muzzle accelerometer were removed and the tube was then impacted at each previous accelerometer location. For ATD-6 the modal hammer was used for the pre-wrap test but for the post-wrap test a 222 N (50 lbf) modal shaker was used to apply the impulse.

The results of this testing for the first three modes can be seen in Table 1. The composite wrap slightly increased the stiffness of the gun. These results were compared to the FEA analysis and were found to be in good agreement. Not only did this result help to validate the FEA models but also ensured that energy was being transferred from the composite to the steel and vice versa.

Table 1 - Modal testing results

	Mode (Hz)								
	ATD 3			ATD 5			ATD 6		
	First	Second	Third	First	Second	Third	First	Second	Third
Pre Wrap	26.50	81.00	174.00	26.00	89.25	169.75	22.50	77.00	165.00
Post Wrap	28.75	85.25	178.75	28.25	83.50	173.75	26.75	80.81	168.80
Post Firing	28.50	85.25	178.75						

The pressure and AE tests were conducted at the same time as they both required pressurizing the gun tube. The pressure test helps to ensure that there is no gap between the steel and the overwrap. If a gap exists then there would be a delay in the composite picking up the pressure load applied to the bore. For the AE test the tube is pressurized twice. The first time there will be some fiber and matrix cracking as any defects need to work themselves out. The second loading should be quiet. If the second loading produces any noise events they could be an indication of damage and need to be investigated.

Standard rosette strain gages were placed at two axial locations along the length of the composite. At each location a gage was placed at the 12, 3, 6 and 9 O'clock positions. The gauges were oriented to record both hoop and axial strain. These same gauges were later used in the firing test. The tube was pressure tested to a peak pressure of 68.9 MPa (10 ksi). The strain readings were recorded every 6.89 MPa (1000 psi) up to peak pressure.

Eight Physical Acoustics R-151 acoustic emission sensors were set up in an F-array so that the location of any suspected damage could be located. The mandrel used to pressurize the tube was only 1828.8 mm (72”) in length so the pressure/AE test had to be conducted twice to cover the entire length of the composite. The strain data collected, during the pressure test, was in good agreement with predictions and within 3% of the FEA analysis.

5. FIRING RESULTS

The guns were taken to Aberdeen Proving Ground (APG) at different times from 2004 through 2007. The guns were fired in direct and indirect fire modes with strain data being taken for the direct fire shots. During these shots a series of two round types were fired at both ambient and hot conditions. Figure 5 is a photo of a direct fire shot.

The test instrumentation used was standard rosette strain gauges. Gauges were placed at two axial locations along the composite area of the tube. At each axial location a gage was placed at the 12, 3, 6 and 9 O'clock positions. Measurements were recorded for the axial and circumferential (hoop) strain. Capturing strain data in this environment can be very challenging so for some firings dozens of rounds were recorded whereas for others only a few rounds of reliable data were captured.

Figure 5 – Test Firing at APG

Table 2 gives both the theoretical and experimental hoop strains for the round types fired. Looking at the table it can be seen that there is good qualitative and quantitative agreement between theoretical and measured strain levels.

For ATD-3, the response for the round type 1 was higher than expected but this is believed to be due to higher than expected pressures generated by the round. The results for round type 2 (the worst case round) were excellent with test results at both locations within 3% of theoretical.

For ATD-5, the response for the hot rounds was higher than expected but this is believed to be due to higher than expected pressures generated by the round. The results for round type 2 ambient were excellent with test results at location 1 being within 1% of theoretical and location 2 being within 5%.

The results for ATD-6 are not as good as the other two. There were many problems with data collection during the test firing so the results are not as good as the other two. The large standard deviations show that there was a large amount of scatter in the data. Still with the exception of location 1, hot the means were within 6% of theoretical.

Table 3–Experimental and Theoretical Hoop Strains

	ATD-3		ATD-5				ATD-6	
Round Type	#1	#2	#1		#2		#2	
		Hot	Ambient	Hot	Ambient	Hot	Ambient	Hot
# of Rounds			8	3	54	3		
Location 1 Experimental	Mean 1755 Std Dev 33	Mean 1766 Std Dev 86	Mean 1693 Std Dev 109	Mean 1931 Std Dev 92	Mean 1724 Std Dev 95	Mean 1758 Std Dev 99	Mean 1819 Std Dev 248	Mean 1930 Std Dev 288
Location 1 Theoretical	1527	1719	1665	1709	1721	1796	1721	1719
Location 2 Experimental	Mean 2160 Std Dev 145	Mean 1933 Std Dev 289	Mean 1863 Std Dev 130	Mean 2258 Std Dev 180	Mean 1690 Std Dev 127	Mean 1771 Std Dev 101	Mean 1792 Std Dev 549	Mean 1806 Std Dev 528
Location 2 Theoretical	1575	1922	1786	1989	1766	1926	1796	1922

For ATD-3, Figure 6 shows the experimental and theoretical strains vs. time at axial location 1 for both round types. Looking at the figure it can be seen again that there is very good agreement for round type 2. For round type 1, the response is higher than expected. As mentioned earlier this is due to the higher than expected pressures.

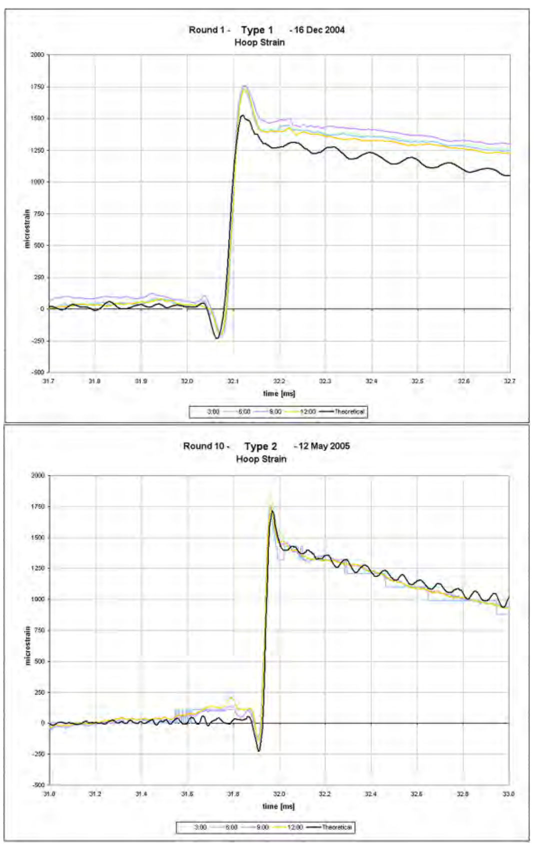

Figure 6–ATD-3 Location 1, Type 1 (left) and Type 2 (right), Strain vs. Time

For ATD-5, Figure 7 shows the experimental and theoretical strains vs. time at both axial locations for both round type 1 ambient. Looking at the figure it can be seen again that there is very good agreement between theoretical and experimental results at location 1. At location 2, it can be seen that the experimental results did not damp out as quickly as predicted but the overall agreement is still very good.

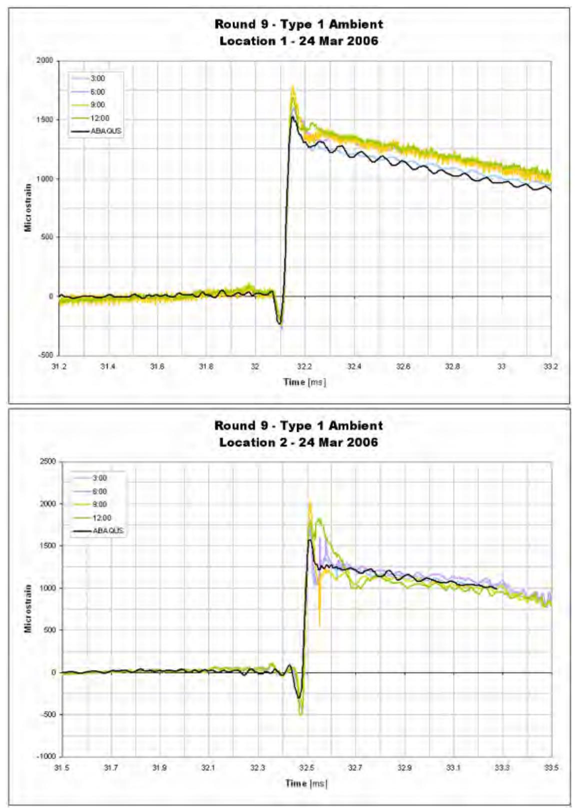

Figure 7–ATD-5 Location 1 (top) and Location 2 (bottom), Type 1, Strain vs. Time

For ATD-6, Figure 8 shows the experimental and theoretical strains vs. time at both axial locations for both round type 2 hot. Location 1 shows very good agreement between theoretical and experimental. At location 2 however there were problems with data collection and the results are nor as good. The trend is still the same but the experimental response was less than predicted.

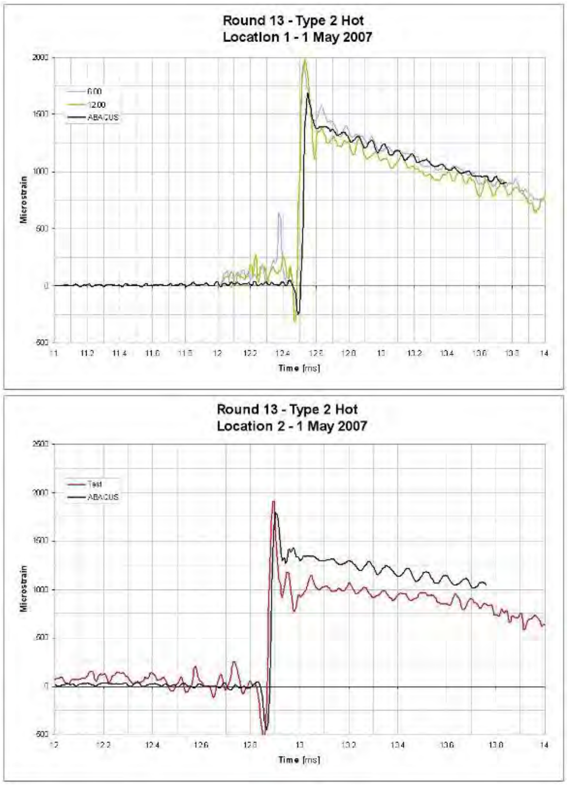

Figure 8–ATD-6 Location 1 (top) and Location 2 (bottom), Type 2, Strain vs. Time

6. FATIGUE TESTING

Before a new cannon system can be fielded it must undergo fatigue testing to establish its safe service life. To generate an interim safe service life (ISFL) two gun tubes must be tested. For the final safe service life (FSFL) an additional four tubes are required. The safe fatigue life testing follows the International Test and Operating Procedure (ITOP) 3-2-829 and the NATO Standardization Agreements (STANAG) 4385. The ITOP establishes the test procedure and the FSFL mathematical calculations. The STANAGs defines the cannon and ammunition pressure terms.

Though this fatigue test was run according to the ITOP and STANAGs the goal was not to generate an ISFL or FSFL. That will be left for future gun tubes. The goals for this test were three fold:

1. To determine the Safe Maximum Pressure (SMP) of a composite section of the tube
2. To verify that the composite wrapped section of the tube will not be the fatigue critical area.
3. To get an idea of how tolerant the composite section is to firing damage.

To determine the SMP the tube section was cycled to increasingly higher pressures until plastic deformation of the bore takes place. This verifies the analysis used to establish the Safe Maximum Pressure (SMP) of the gun tube. The piece test was a composite wrapped autofrettaged section, with the same goals.

As part of the ITOP procedure the chamber section and other high risk sections must be fatigue tested. Ideally one would like the chamber to be the only high risk section that way only the chamber sections must be fatigue tested. Simulations suggested that the composite wrapped section would not be a high risk section but, since composite wrapped gun tubes are new, two pieces of the composite section were tested. The first section was taken from the autofrettaged zone of the tube; the second section from the non-autofrettaged zone. These sections were cycled to 10,000 cycles or failure, whichever came first.

There has been some concern that a composite wrapped tube would be more susceptible to small arms fire than an all steel gun tube. To test this, a section of the tube would be shot with a small caliber round, causing a glancing blow, damaging the composite but not the steel. The section would then be cycled 100 times.

The fatigue test is conducted under quasi-static loading conditions so crack initiation must have occurred prior to test commencement. The 250 round firing test discussed in section five was used to establish the required heat checking and crack initiation. Previous work (Racicot et al., 1973) has shown that if heat checking and crack initiation is present then one cycle in the lab is equivalent to one round fired in the field.

After the gun tube was received it was cut into test sections and seal pockets were machined into the ends of the sections. Strain gages were mounted to the outside of the sections to monitor the hoop strains generated. A filler bar was placed inside the section to minimize the amount of oil that must be pressurized. An end closure with seal assembly was installed in the both end seal pockets, covering the entire circumference of the seal pocket. The entire assembly was then placed into the press.

The composite section SMP and fatigue tests were performed in our 13.3 MN (3000 kip) press. High pressure fluid was introduced from the pre-load reservoir (for initial seal seating) and from a high pressure intensifier, into the test specimen, through ports in the end closures. There is a calibrated pressure sensor placed in the high pressure piping, close to the test specimen for monitoring the test pressure. A digital readout is connected to the pressure transducer and viewed by the system operator during testing. For the SMP test pressure was applied to the specimens in steps, held for a few seconds in order to collect all strain reading. For fatigue testing the pressure was cycled from a low to high setting until the desired number of cycles was reached of the specimen failed. The time for one pressure cycle was approximately ten seconds. Figure 9 shows a composite section in the press.

Figure 9–Composite Section in Press

The composite SMP test produced the expected results. The autofrettaged composite test section failed at a much lower cycle count then expected. However in reviewing the test data it was determined that it was cycled at a much higher pressure then it should have been. When this was taken into account the result matched with predictions and indicates that it will not be a fatigue critical portion of the tube. The non-autofrettaged section survived all 10000 fatigue cycles without failure.

For the damage tolerance test, the non-autofrettaged composite section was shot with a 7.62mm armor piercing round. This was done at a glancing angle to cause damage in only the composite and not the steel. The section was then placed in the press and cycled 200 times without failure. This indicates that the composite has come degree of damage tolerance and that the gun tube has the potential to continue firing even after sustaining minor battle damage.

Overall these initial fatigue test results are very promising though there are still some unanswered questions. A degree of damage tolerance has been demonstrated, but further work in this area should be conducted. No major issues with the composite wrapped sections and fatigue life were uncovered. This bodes well for future composite wrapped tubes to achieve an FSFL in line with requirements.

7. CONCLUSION

Three lightweight composite wrapped 120mm gun tubes were successfully designed, manufactured, and test fired. A thermoplastic matrix was used, allowing for cure in place fabrication. This avoided the manufacturing complications due to coefficient of thermal expansion mismatch encountered in previous attempts at composite wrapped gun tubes. The prepreg was applied under tension resulting in a favorable prestress in the composite jacket. The design resulted in a gun tube that was 205 lbs lighter than its all steel counterpart while maintaining the same first bending mode and cross sectional profile.

Finite element models were used to help predict the response of the gun tube to firing loads. These models were validated through non-destructive testing and later shown to be in good agreement with the firing results. The composite jacket survived the firing with no apparent damage. The fatigue tests were conducted and the results did not uncover any major issues. The preliminary fatigue results bode well for future composite wrapped tubes to achieve an FSFL in line with requirements.

Overall, this effort was very successful and the data collected will be very useful in the design of future composite wrapped gun tubes. In fact the basic design was selected as the baseline design for the main armament for the Future Combat Systems-Mounted Combat Systems vehicle. The design was undergoing more detailed testing / optimization under the System Design and Development portion of that program when Future Combat Systems was cancelled.

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