Army Research Laboratory

Refractory Metal Liner Processing for M242 Medium Caliber Barrels

by William S. de Rosset and David Gray

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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT
The process for attaching a refractory metal liner to a gun tube, known as Gun Liner Emplacement with an Elastomeric Material (GLEEM) has been developed for the 25 mm Bushmaster medium caliber cannon. Stellite 25 liners were emplaced in three barrels. The liners in the first and third barrel were rifled, which enabled them to be fired. A small amount of liner extension was observed in each of the fired barrels. Sectioning of these barrels revealed that the liner extension was due to both liner displacement and liner stretching.

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1. Introduction

For the past several years, a process to bond refractory metal liners to gun tubes has been under development (*1–3*). Known as Gun Liner Emplacement with an Elastomeric Material (GLEEM), the process has been used to attach a variety of metal liners to the insides of short lengths of steel cylinders. Although the work on this project began in 2006, it took until 2011 for a patent to be granted (*4*). Up to this point, only laboratory steel cylinders had been used. However, the ultimate goal is to demonstrate the use of the GLEEM process to emplace a liner in an actual gun. To this end, three medium caliber M242 cannons were obtained from Benét Laboratories, Watervliet, NY, with the intention of emplacing a Stellite 25 liner in each one. This is the subject of this report.

In preparation for the scale-up, experiments using short, unlined tubes were conducted prior to processing the M242 barrels. These experiments will be described briefly in section 2. Next, the Stellite 25 liners were ordered. Section 3 provides the details concerning how the dimensions of these parts were determined. Section 4 describes some preliminary experiments on short cylinders that were used to see what sort of problems there might be and determine the best course of action. Section 5 provides the details of the actual M242 barrel processing. The development of the process proceeded by a trial-and-error process. What was learned from processing the first barrel was applied to the second and so forth. Results from firing trials are presented for the first and third barrel. Up to now, the longest tube that had the GLEEM process applied to it was 12 in. In order to make the problems more tractable, the M242 gun tubes were truncated at 3 ft. It was assumed that the same procedures used to GLEEM these tubes could be used for full length tubes.

Two more issues remained before the GLEEM process could be considered successful. First, the Stellite 25 liner had to be machined after emplacement. To the best of our knowledge, the machining of lands and grooves in a Stellite 25 liner in a medium caliber cannon had never been done. ARES, Inc., Port Clinton, OH, was selected to develop the tooling for this task, based on their success in machining lands and grooves in a tantalum-10% tungsten liner explosively bonded to an M242 gun tube (*5, 6*). Second, while some initial estimates of the bond strength needed to overcome the forces on the liner during actual shooting had showed the bond strength to be sufficient, there had been no actual gun firings of a liner emplaced by the GLEEM process.

There were many lessons learned in scaling up the GLEEM process. Preliminary experiments were conducted on laboratory steel tubes that answered several questions. This is covered in section 2. Calculations had to be made that determined the initial dimensions of both the liner and gun barrel so that the processing would result in dimensions suitable for machining the lands and grooves. This is covered in section 3. The processing parameters had to be estimated from information gained in previous tests. This is presented in section 4. The actual scale-up process is described in section 5. The results of the firing tests are provide in section 6. The results are discussed in section 7, and a summary of the work is presented in section 8.

2. Preliminary Experiments

In order to apply the GLEEM process to emplace a Stellite 25 liner into a truncated M242 Bushmaster medium caliber cannon, the liner was pressurized in short sections to avoid possible frictional effects that might occur if the entire liner were to be pressurized at one time. The experimental procedure for this process was developed using 12-in long 4340 steel cylinders. The cylinders had an outer diameter of 3 in and had a center hole with a 1-in diameter. There was no liner for these tests.

In anticipation of processing a 3-ft tube, an Instron/SATEC one-million pound force compression load frame was used to process the 12-in cylinders. This particular load frame had an opening that would accommodate the truncated M242 tube. These tests also provided the opportunity to become familiar with the Digital Image Correlation (DIC) instrumentation in this particular test environment, as well as the software that was used to program the ramp rates and hold time for the load frame.

The first cylinder was pressurized in three sections. In order to do this a 9-in steel load rod had to be used to transfer the load from the load frame to the first 4-in elastomer section and seals. A schematic of the test arrangement for the first section is shown in figure 1.

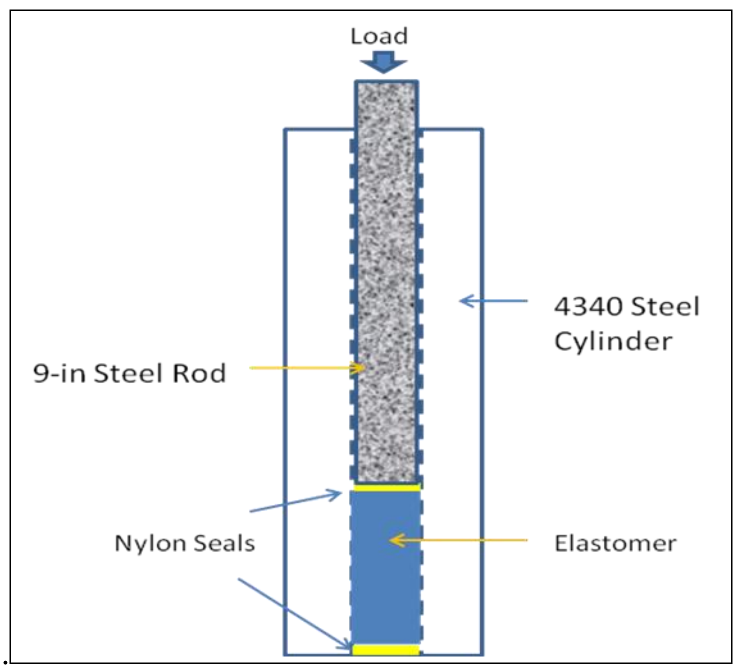

Figure 1. Experimental setup of the first pressurization.

After pressurization and with the elastomer section and seals retained in the steel cylinder, a second 4-in elastomer section (with a top nylon seal) was inserted into the steel cylinder. In effect, the combined length of elastomer was approximately 9 in, counting the seals. The elastomer used in these experiments was Dow Corning Silastic[1] RTV (room temperature vulcanization). A 5-in steel load rod was then used to transfer the load to the elastomer section. The final elastomer section was inserted into the steel cylinder and contacted the nylon seal of the second plug; the third section was loaded in the usual manner.

DIC was used to measure several components of strain over a large area of the steel cylinder's surface. In this measurement technique a speckled pattern is applied to the surface of the steel cylinder; two cameras are used to produce stereo-optic image of the cylinder surface. As the cylinder expands due to the pressurization, the speckle pattern is distorted, and the image can be analyzed by computer software to measure the components of strain. A picture of the experimental setup is shown in figure 2. Details of the test fixture used in the GLEEM process can be found in (*7*).

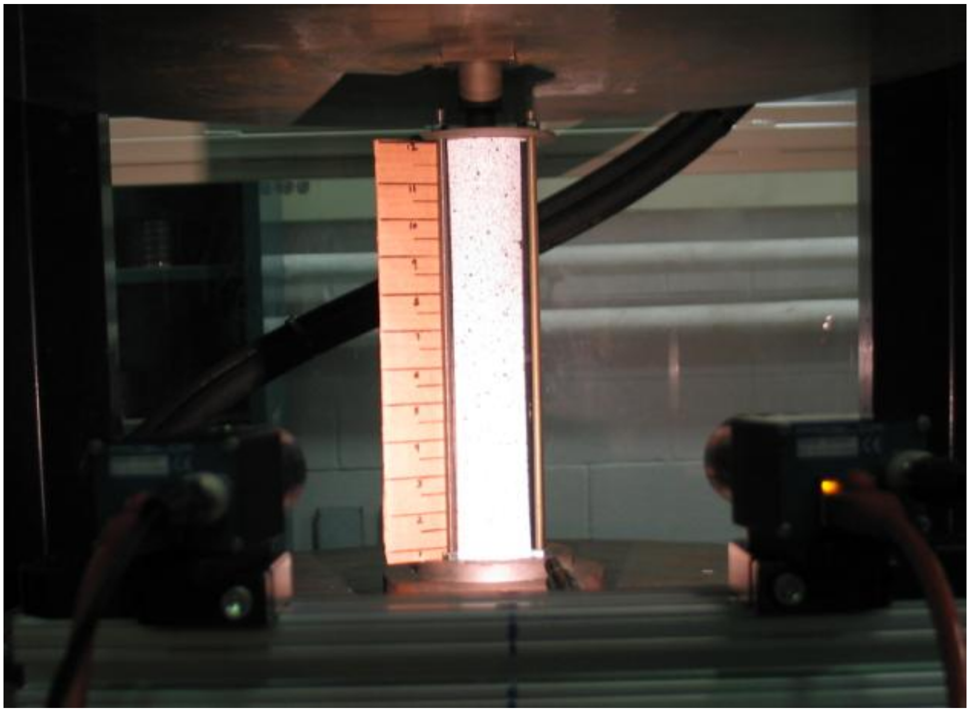

Figure 2. Experimental setup of DIC strain measurement using the GLEEM testing fixture as detailed in (*7*).

A compression load of 120,000 lb was used for the first cylinder which produced an internal pressure of 152.7 ksi, assuming no frictional effects. This was below the yield point of the steel, assumed to be 160 ksi. Hoop strain measurements are shown in figure 3, taken at the time the maximum load was applied to the elastomer. The origin of the plot is the bottom of the cylinder.

[1]Silastic is a registered trademark of Dow Corning Corporation.

(One-half inch of the bottom of the cylinder is masked by the test fixture, so strain measurements at the very bottom could not be made.) After removal of the elastomer and seals, measurements of the inner diameter of the steel cylinder were taken with a telescoping gage. There was no indication plastic deformation.

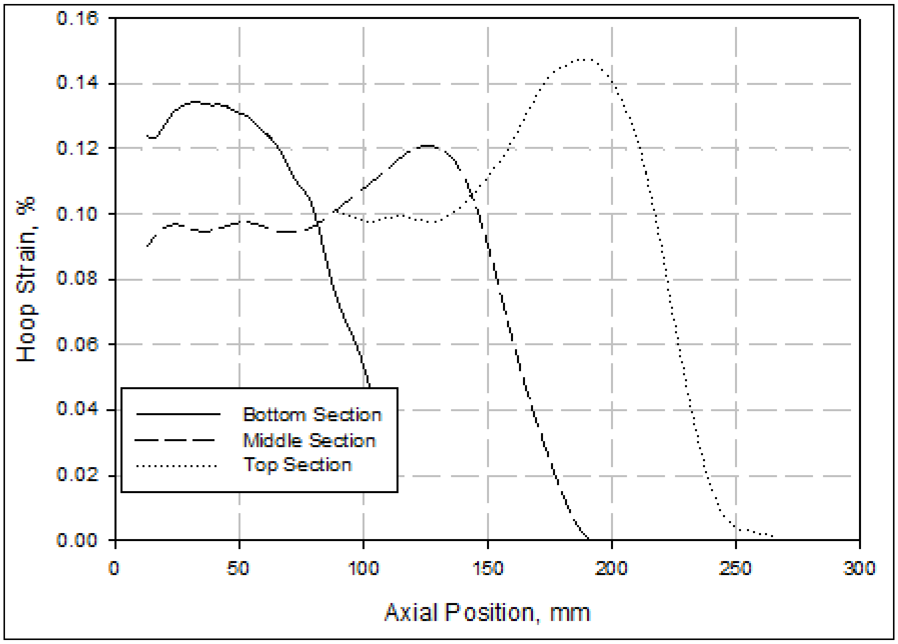

Figure 3. Measured hoop strain as a function of axial position for first 12-in steel cylinder.

A second steel cylinder was pressurized using an 8-in elastomer section and a 4-in elastomer section. In choosing the 8-in length, a compromise was made. On one hand, the length had to be long enough to reduce the number of steps that would be needed for the truncated M242 tube. On the other hand, the length had to be short enough to reduce the effects of friction down the length of the elastomer section. A compression load of 160,000 lb was used for the second tube in order to obtain some plastic deformation of the steel cylinder; this load gave an internal pressure of approximately 204 ksi. DIC measurements were also used to obtain the strain components on the outer surface of the steel cylinder. Results are shown in figure 4. After the GLEEM process had been applied to the cylinder, measurements of the inner diameter of the steel cylinder were made. There was no noticeable enlargement of the cylinder.

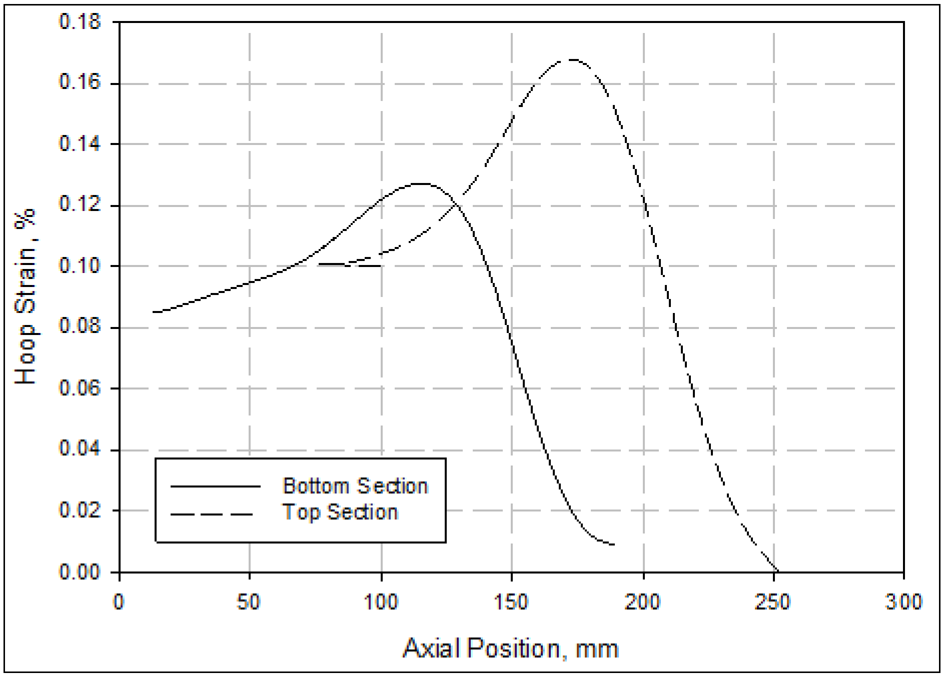

Figure 4. Hoop strain measurements as a function of axial position for the second steel cylinder (8-in and 4-in plugs).

The fact that very little permanent deformation of the steel took place on any of the tests led to the supposition that the steel had a higher strength than 160 ksi. A slice was taken from the second steel cylinder and the hardness measured on the Rockwell C scale. An average of 10 measurements yielded a hardness of 43.7 HRC, corresponding to tensile yield strength of 200 ksi (*8*). The lesson learned from the preliminary experiments was always to measure the hardness of the barrel that is to be processed by GLEEM.

During the GLEEM process, the load rod is displaced a certain distance as the elastomer compresses. (Actual rod displacements will be given in section 5.) The distance will depend on the length of elastomer in the cylinder. At the maximum displacement of the load rod, there is no pressure on the cylinder wall from the initial to the final position of the leading surface of the load rod. In the plots shown in figure 4, the liner is not pressurized from about 250 to 300 mm. In order to fully process the cylinder, the elastomeric material and seals must be removed from the cylinder and the process started from the other end.

A lesson learned during the preliminary phase of the scale-up was that the nylon seals had a tendency to extrude into the space between the load rod and tube wall. The load rod became stuck and had to be extracted with a hydraulic press. This was facilitated by drilling and tapping a hole in the top end of the load rod.

3. Liner and Barrel Dimensions

Several GLEEM experiments had previously been conducted with a Stellite 25 liner inside a steel cylinder (*3*). The dimensions used in these experiments closely approximated those that were to be used in the application of GLEEM to the M242 gun barrel. These tests indicated that the pressure exerted by the elastomer on the liner and gun tube achieved maximum bond strengths for pressures between 218 and 247 ksi (1500 and 1700 MPa). At these pressures, the Stellite 25 liner inner diameter had a permanent increase of approximately 2.5%. The final liner diameter at the land location in a finished M242 barrel is 25.019 mm (0.985 in). Consequently, the inner diameter of the as-received Stellite 25 tube was chosen to be 24.13 mm (0.950 in). Given an increase of 2.5%, this would result in a final inner diameter of 24.73 mm (0.974 in). This allows a honing operation to be performed on the liner to achieve the final dimension of 25.019 mm (0.985 in) for the inner diameter at the land location.

The depth of the grooves in the M242 is 0.51 mm (0.020 in). For the current work, a liner thickness of 1.3 mm (0.05 in) at the groove location was selected. This thickness is much higher than that calculated to be the minimum thickness required to prevent phase transformation of the gun barrel steel due to thermal loading (*9*). Note also that this thickness is about ten times that of the chrome coating used in large caliber guns. The actual liner thickness at the groove location will depend on the amount the liner is stretched from its original configuration and how much of the liner is honed. Thus, 1.3 mm (0.05 in) is simply a dimension that can be used to determine the original liner thickness and may not be what is finally achieved. Given a groove depth of 0.5 mm (0.02 in), the initial liner thickness at the land location is 1.8 mm (0.071 in). This makes the final outer diameter of the Stellite 25 tube to be 27.69 mm (1.090 in).

Three M242 barrels were obtained from Benét Laboratories. The barrels had been retired from service due to extensive wear. The U.S. Army Research Laboratory (ARL) machine shop sectioned each barrel, leaving a length of 965 mm (38 in).

Three Stellite 25 tubes were purchased from True Tube of Paso Robles, CA. The dimensional specifications requested were 1.090” ± 0.002” OD by 0.950” ± 0.002” ID by 36” long. The M242 barrels were honed to produce a slip fit of the liner into the gun tube. There was a short length of liner (~3 in) that extended into the chamber of each gun tube. It was planned to machine away this excess material after the gun tubes had undergone the GLEEM process.

4. Initial Considerations

Based on the experience gained during the preliminary experiments, the hardness of the first truncated M242 barrel was measured. A thin ring of material was cut from the muzzle end and hardness measurements were taken at various locations on the flat surface of the ring. These measurements resulted in an average hardness value of HRC 37.2. This hardness value converts to a tensile yield strength of 169.8 ksi (1170 MPa).

The amount of force applied to the load rod depends on the tube wall thickness and will be different for each step. The intent is to apply enough pressure so that the gun tube is plastically deformed throughout its thickness. The pressure P_i needed to do this is given by

$$P_i = \sigma_y \ln(b/a), \tag{1}$$

where σ_y is the yield strength of the steel, b is the outer radius of the gun tube, and a is the radius of the liner. The differences in material properties of the liner and gun tube have been ignored. So long as the length of elastomer is short enough (i.e., 8 in), we can estimate the pressure P in the elastomer from the following:

$$P = \frac{L}{\pi h^2}, \tag{2}$$

where L is the applied load and h is the load rod radius. In the present case, h = 12.0 mm (0.4725 in). As an example, the muzzle end of the truncated barrel had an outer radius of 32.04 mm (1.26 in). The outer radius increases to 36.07 mm (1.42 in) approximately 200 mm (7.9 in) towards the breech end. Therefore, the smaller of these radii must be used to determine the applied load. Equating P_i to P, we get

$$L = \pi h^2 \sigma_y \ln(b/a). \tag{3}$$

Using 170 ksi as the yield strength, we get $L = 5.18\text{x}10^5$ N (116500 lb). For an outer barrel radius of 38.1 mm (1.5 in), $L = 6.09\text{x}10^5$ N (137000 lb). We expect the hoop strain measurements at the highest load to be approximately 0.2%, signaling the onset of plastic deformation at the outer surface of the gun tube.

A set of four load rods of different lengths was made to accommodate the different steps in the GLEEM process. They were made of 4340 steel bars, hardened to 50 HRC. This hardness value corresponds to a yield of 233 ksi (1605 MPa). The highest compressive stress applied to the load cylinders was expected to be 193 ksi (137 kips/π/0.475^2), still within the elastic range of the material.

Another possibility of load rod failure was buckling. In an ideal situation, the maximum load that the load rod can withstand without buckling, F_b, can be determined from Euler's formula:

$$F_b = \pi^2 EI/(K\lambda)^2, \tag{4}$$

where E is the elastic modulus of the 4340 steel, I is the area moment of inertia, λ is the unsupported load rod length, and K is the column effective length parameter. K depends on how the ends of the rod are supported. Assume that the GLEEM process corresponds to having one end of the load rod fixed (the end inside the liner) and the other end pinned (free to rotate). In this case, K = 0.699 (*10*). Also,

$$I = \pi(0.475)^4/4. \tag{5}$$

Taking E = 29700 ksi (2.05 GPa), we plot F_b versus λ in figure 5.

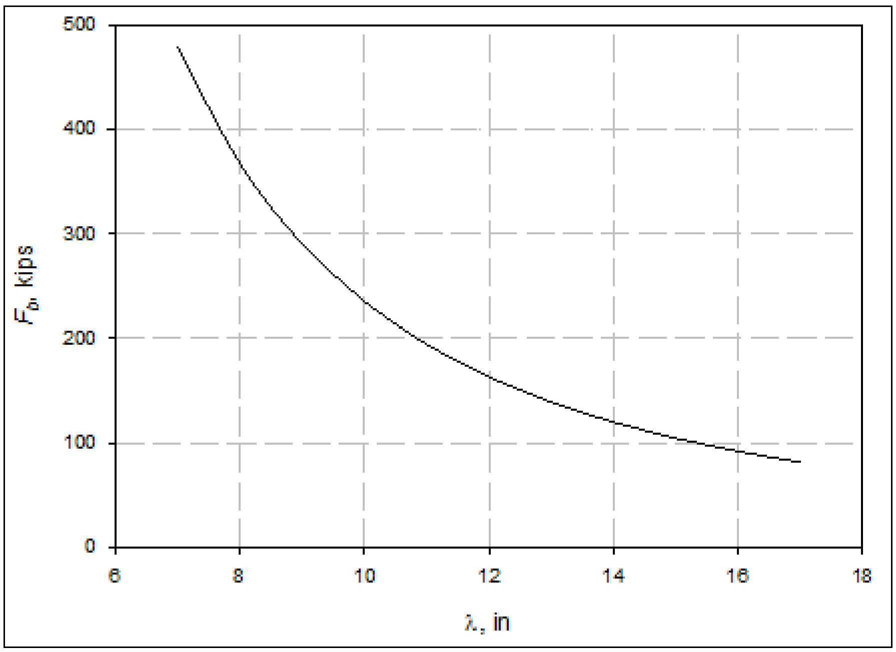

Figure 5. Buckling load versus unsupported length.

The greatest load expected for the GLEEM process in this particular case is 137 kips. Therefore, so long as the unsupported length is less than 10 in, there should be no buckling failure. The question arises as to how much support the Stellite 25 liner supplies. With a clearance of 0.0025 in between the load rod and Stellite 25 liner, there should be no buckling within the liner. However, the effective unsupported length may be somewhat greater than the length of load rod extending outside the liner.

5. Barrel Processing

5.1 First Barrel

GLEEM processing of the first barrel called for four passes or loadings of the elastomeric material. However, several passes had to be repeated, resulting in a total of eight separate passes being made. The general approach was to use an 8-in long solid bar of Teflon[2] with a diameter of 1.088 in as the elastomeric material for each pass. Nylon seals were used at each end of the bar. The muzzle end of the barrel was the first portion processed. A picture of the barrel inside the holding fixture is shown in figure 6. The speckle pattern was used for the DIC measurements.

Figure 6. Truncated gun tube in GLEEM testing fixture at full scale.

[2]Teflon is a registered trademark of E.I. Du Pont de Nemours and Company.

The first pass made use of a 33-in load rod. With the elastomeric material and seal in the gun barrel, this left 3.5 in of the load rod unsupported outside the gun barrel. The chamber length is 4.4 in, and since its diameter is much larger than the bore, the load rod was not supported within the chamber. This resulted in a total of 7.9 in of unsupported length. A load of 124,000 lb (124 kip) was maintained on the elastomer for 30 min.

Real-time strain readings indicated that there was an insufficient amount of strain being imparted to the cylinder. The load was increased to 130 kip, at which point the load rod failed. (In order for the load rod and gun tube to be in alignment with the load platen, the load rod and gun tube assembly has to be vertical. If the assembly is not exactly vertical, then the ideal conditions used to compute the buckling load are not present.) Later analysis of the strain data showed that a reasonable level of strain had been achieved at the muzzle end of the gun tube during the first pass.

For the second pass, another 8 in of Teflon was added to the elastomeric column. A 26.5-in load rod was used to apply a 138 kip load to the elastomer for 30 min. The total unsupported load rod length was 9.9 in.

Experimental difficulties were experienced when the third 8-in Teflon bar was added. A 15-in load rod was the first used. This proved to be too short, and a spacer rod was inserted between the load rod and test machine for the next attempt. Unfortunately, as the maximum load was approached, the spacer rod was ejected from the load machine, and the pass was halted. The next attempt was made with a 20-in load rod. A loud noise was heard during the pass, and it was halted before the maximum load was achieved. It was found that the load rod had been inserted with tapped end next to the elastomer, which extruded into the hole.

During the next pass with the 20-in load rod, the rod bent at a load of 120 kip. The unsupported length was 11.4 inches. Again, the cause of the failure may have been incorrect alignment of the push rod. The next attempt was made with a 17.5-in load rod. This load rod also bent, although at a higher load (135 kip).

For the last pass, the gun barrel was inverted, all the elastomer removed, and an 11-in Teflon bar inserted into the breach end of the liner. A steel rod supported the elastomer, as shown in figure 7. A 26.5-in load rod was used to apply a load of 130 kip for 30 min to the elastomer. Note that since the gun barrel was inverted, the load rod did not pass through the gun chamber. Consequently, the unsupported length was much lower than those for the other passes. This completed the processing of the first gun barrel.

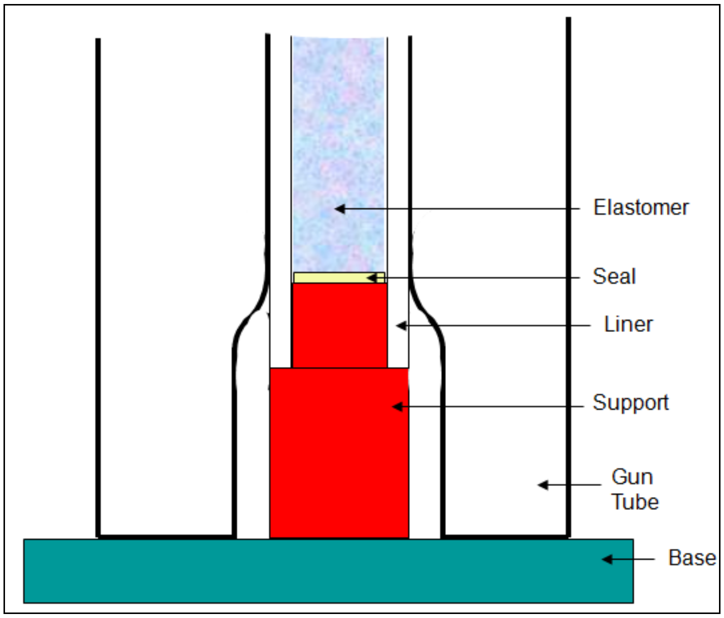

Figure 7. Details of support arrangement (not to scale).

Table 1 summarizes the data obtained from the eight passes. The data listed as initial unsupported length in the fourth column are the lengths of the load rod outside the liner at the beginning of the pass. The load rod displacement is shown in the fifth column. Note that the unsupported length at the maximum load would be the difference between the values in columns four and five. The maximum hoop strain, taken from the DIC data, is representative of the hoop strain near the center of the viewing area for a given pass.

Table 1. Selected data for first barrel.

Pass Number	Load Cylinder Length (in)	Maximum Load (kip)	Initial Unsupported Length (in)	Load Rod Displacement (in)	Maximum Hoop Strain (%)	Result
1	33	124	7.9	1.9	0.17	Pass completed
2	26.5	138	9.9	3.9	0.13	Pass completed
3	15	112	6.4	3.3	0.10	Test halted- interference with load frame
4	18	127	9.4	3.1	0.11	Test halted-spacer rod came out
5	20	112	11.4	5.2	0.12	Test halted- load rod incorrectly place
6	20	120	11.4	3.1	0.13	Load rod bent
7	17.5	135	8.5	3.5	0.17	Load rod bent
8	26.5	130	4.9	2.3	0.25	Pass completed

In those cases where the load rod bent, the load rod was observed to begin deforming gradually before it failed. The suspicion was confirmed in later tests that the initial deformation was caused by a slight misalignment of the load rod and gun tube. Any misalignment is inconsistent with the assumptions going into the calculation of buckling load. In any event, it is clear that minimization of the unsupported length is quite important.

The barrel was shipped to ARES, Inc. of Port Clinton, Ohio for them to machine the lands and grooves in the liner with the standard pattern for an M242 barrel. In addition, they machined the end of the liner so it made a smooth transition into the chamber area.

5.2 Second Barrel

For the second barrel, steps were taken to reduce the possibility of load rod failure. First, new load rods of S-7 tool steel were made and hardened to over HRC 50. The outer diameter of each load rod was increased to 0.945 in (24.00 mm) to decrease the space between the load rod and the Stellite 25 liner. Second, the gun barrel was processed starting at the breech end. This eliminated the need for the load rod to pass through the gun chamber on the first passes. Four passes were used in this configuration. The elastomer length in the first three passes was 8 in (203.2 mm), and the length was 4 in (101.6 mm) on the fourth pass. On the fifth pass when the barrel is inverted, the load rod must pass through the gun chamber. However, since the muzzle end of the barrel is being processed in this step, the load is lower. A schematic of the steps is shown in figure 8. The fourth pass is omitted due to space constraints. Note that the schematic does not include the clamping arrangement shown in figures 2 and 6. The clamping arrangement was used to insure that the elastomer does not escape from the liner. This arrangement consisted of a top plate and a bottom plate (base support) connected by four rods. In addition, there is a ¾ in (19.1 mm) plate inserted between the load rod and the load frame. This plate had a shallow recess machined into it, approximately 1/8 in deep (3 mm). The push rod fit into this recess. The recess helped to pin the top of the push rod to the plate.

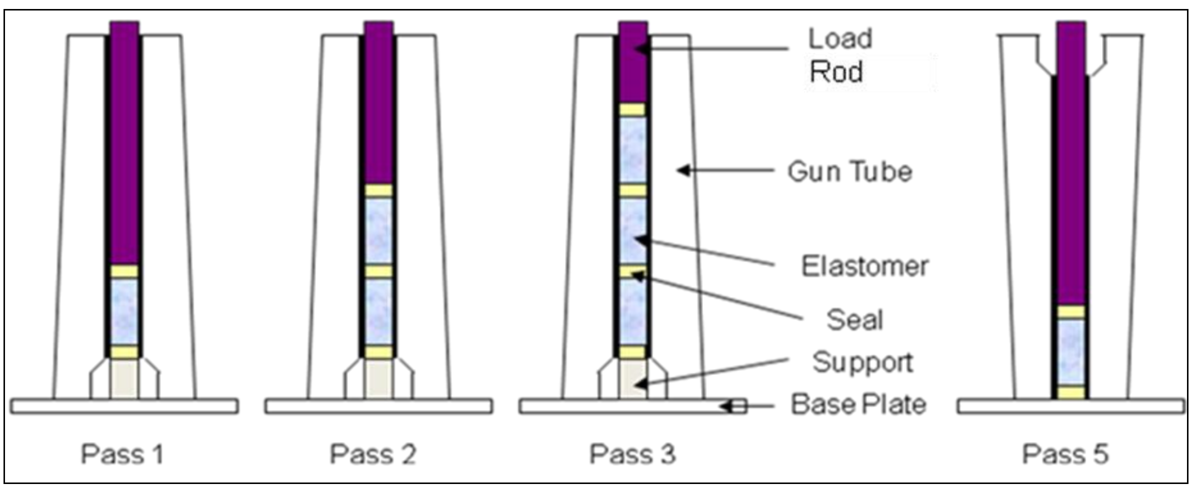

Figure 8. Schematic of processing scheme.

The first four passes used the same support shown in figure 7.

In actual practice, the steel forgings used to make the M242 tubes would have the GLEEM process applied to them before final machining was performed. Note, however, that using finished barrels in this work would demonstrate the possibility of refurbishing old barrels that had been taken out of service due to barrel erosion.

An incorrect length load rod was used on the first pass for the second barrel, and before a load of 136 kip was obtained, the load rod bent. The procedure was halted and re-examined. Since the unsupported length was still well below that needed to buckle the rod, it was conjectured that a slight misalignment of the gun tube was causing premature failure of the load rod. It was decided that a better way to align the gun tube in the load frame was needed. A new base fixture, shown in figure 9, was designed to allow small adjustments in the angle the gun tube made with the load frame (*11*). A Pro 3600 digital protractor was used to assure that the gun tube was vertical to ±0.1 degree. In addition, two dial indicators were positioned 90° to each other to indicate motion of the gun tube during processing. With these improvements, the first four passes were successfully completed. The load was ramped to 136 kip at a rate of 10 kip/min and held for 30 min. Load release occurred at a rate of 15 kip/min. The gun tube was then inverted and a fifth pass attempted. For this pass, straps were applied to the gun tube to prevent a large motion and possible damage to the load frame. Approximately 15 min into the hold portion of the pass, the dial indicators began to indicate rapid gun tube deflection, and the test was halted. It was later determined that the bottom nylon seal had been extruded out of the gun tube and was the possible cause of the gun tube starting to tip. The load rod was slightly bent at the end with the tapped hole. The indicators successfully detected motion before any gross movement of the gun tube occurred.

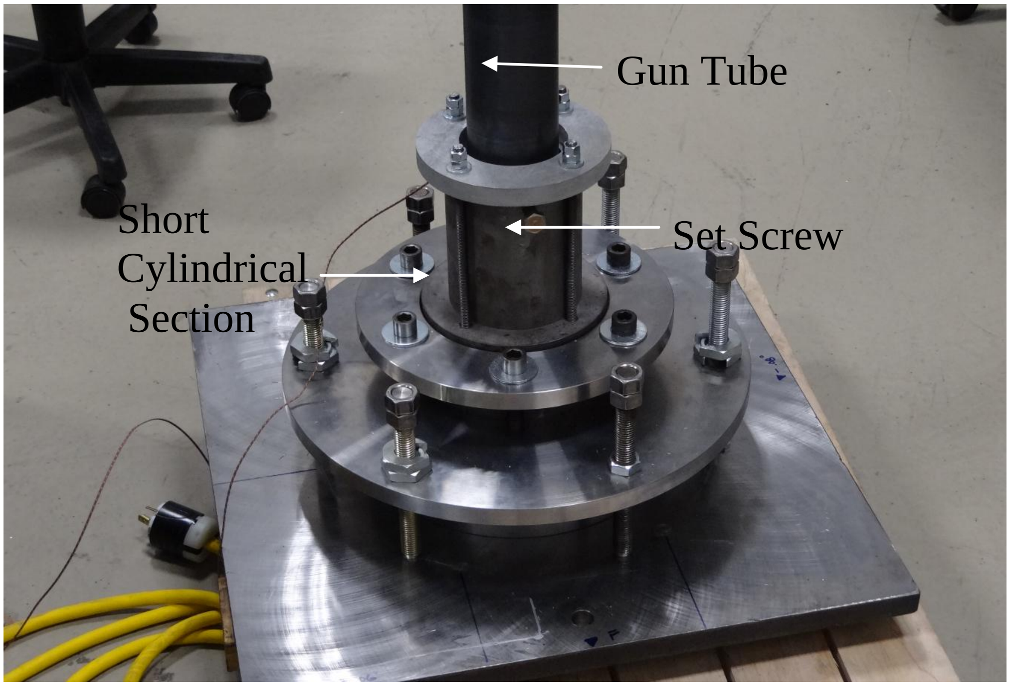

Figure 9. Gimbaled base alignment test fixture for M242 gun tube.

The inner diameter of the liner was measured a short way in from both the muzzle and breech ends. These measurements indicated that the liner had expanded approximately 0.5% at the breech end and 1% at the muzzle end. The breech end measurements may have had a larger error, since the depth gage had to pass through a narrow portion of the liner that may have constricted it on the way out of the tube. This was not the case with measurements made at the muzzle end of the liner.

5.3 Third Barrel

During the test firing of the first barrel, the liner was observed to extend in the tube (see section 6.1). Based on these results, the Stellite 25 liner was modified in an attempt to keep it in place during firing tests of the third barrel. The rear end of the Stellite 25 tube was cold sprayed with pure nickel, then machined so that it could fit precisely inside a matching surface of the gun tube. The small shoulder was expected to provide enough resistance to the keep the liner in place during the firing trials. Figure 10 shows the end of the Stellite 25 tube after it has been cold sprayed.

Figure 10. Picture of Stellite 25 tube with nickel cold-sprayed at one end (not machined).

A lesson learned from processing the second tube was to machine the muzzle end of the gun tube flush with the liner. This helped to prevent extrusion of the seal out of the gun tube during the fifth pass.

The processing of the third barrel was completed without incident. For each of the first four passes, a constant load of 136 kip was applied for 30 min. The fifth pass employed a load of 124 kip. The ramp rate to the constant load was 10 kip/min in each case. The load was released at a rate of 15 kip/min. As before, special attention was paid to keeping the gun barrel as vertical as possible.

During the ramp to constant load, the load rod is displaced a certain amount. It continues to move during the hold time. These displacements are shown in table 2 for the third barrel along with similar measurements for the second barrel. The initial displacement is the amount the load cylinder moves during the load ramp-up. The final displacement is that at the end of the hold phase. The numbers for the two barrels are in reasonable agreement.

The third barrel was sent to ARES, Inc. for final machining of the lands and grooves. It was returned to ARL where firing tests were conducted.

Table 2. Load rod displacements.

	Barrel 2		**Barrel 3**	
	Initial Displacement (in)	**Final Displacement (in)**	**Initial Displacement (in)**	**Final Displacement (in)**
Pass 1	1.772	1.823	1.814	1.867
Pass 2	2.809	2.931	2.846	3.004
Pass 3	3.548	3.709	3.560	3.765
Pass 4	3.574	4.030	3.865	4.089
Pass 5	1.811	1.864	1.848	1.909

6. Firing Tests

6.1 First Barrel

After the first barrel was machined at ARES, Inc., five test rounds were fired with M791 ammunition at their indoor range. A slight extension of the liner from the muzzle end of the barrel was observed after the first shot. The extension continued to grow as the barrel was fired. After firing, the barrel was sent back to the ARL. The total amount of liner extension past the end of the barrel was measured to be approximately 0.026 in. The exact value depended on where the measurement was taken. Examination of the interior of the rear portion of barrel with a borescope was inconclusive. The smooth transition of the liner into the bore area masked the possible movement of the liner.

Firing of the first barrel continued in test facility 162A, building 390 at ARL. After the first shot, the liner extension out of the barrel was measured at a particular spot. Measurements were taken at this position for the remainder of the tests so that a consistent set of values was obtained. The results are shown in figure 11. The measurement taken after the eighteenth shot was 0.082 in. While the rate of liner extension out of the tube appeared to be decreasing with the shot number, it was still too large to be acceptable. A least squares fit to the data indicated that the liner moved 4.3×10^{-3} in (1.6×10^{-4} mm) per shot.

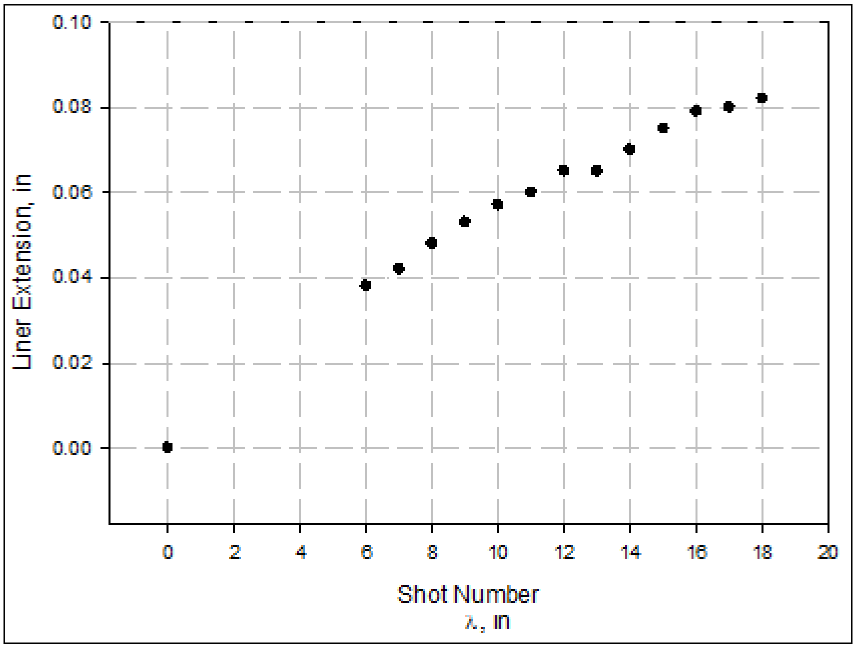

Figure 11. Liner extension versus shot number for barrel number 1.

6.2 Third Barrel

The third barrel was machined at ARES and sent to ARL for testing at the same facility where the first barrel was fired. After three firings with M791 ammunition, there did not appear to be any liner extension. On the fourth shot a small amount of extension could be detected although it was too small to measure. Tests continued until 15 shots were fired; at that point, the liner extension was measured to be 0.012 in (0.30 mm). Tests were halted until more ammunition was obtained.

When test firing resumed, multiple measurements of the barrel extension were made. A dial caliper depth gage was used to record the liner extension at four points around the circumference of the liner. These measurements were then averaged to give a final value.

After 16 more firings, the firing pin in the breech mechanism broke, and tests were suspended until a new firing pin could be obtained. When testing resumed, the remaining 14 shots were fired. Figure 12 shows the measured liner extension as a function of shot number. A least squares fit to the linear portion of the curve indicated that the liner moved 1.7×10^{-3} in (6.7×10^{-5} mm) per shot. Figure 13 is a photograph of the muzzle end of the gun tube showing the liner extension after completion of all the firing tests.

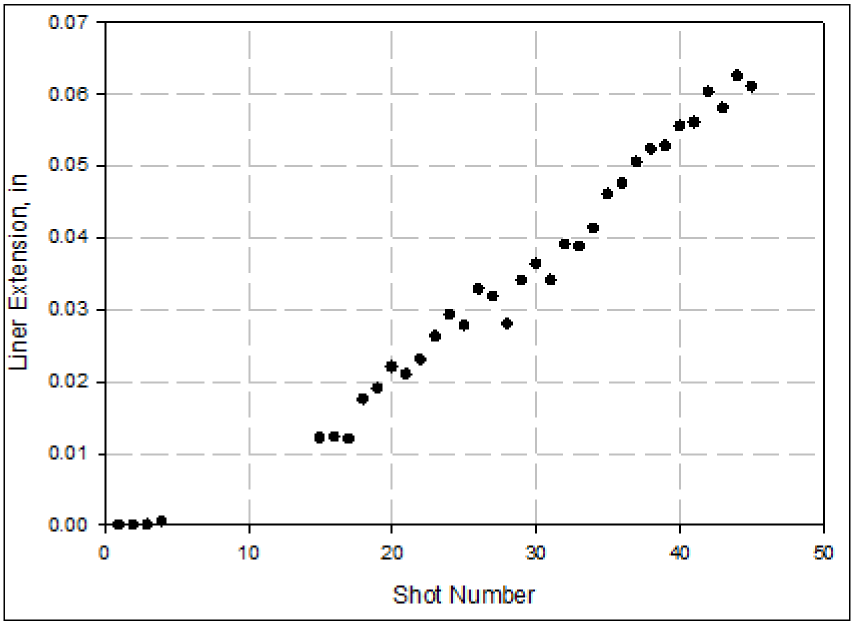

Figure 12. Liner extension versus shot number for barrel number 3.

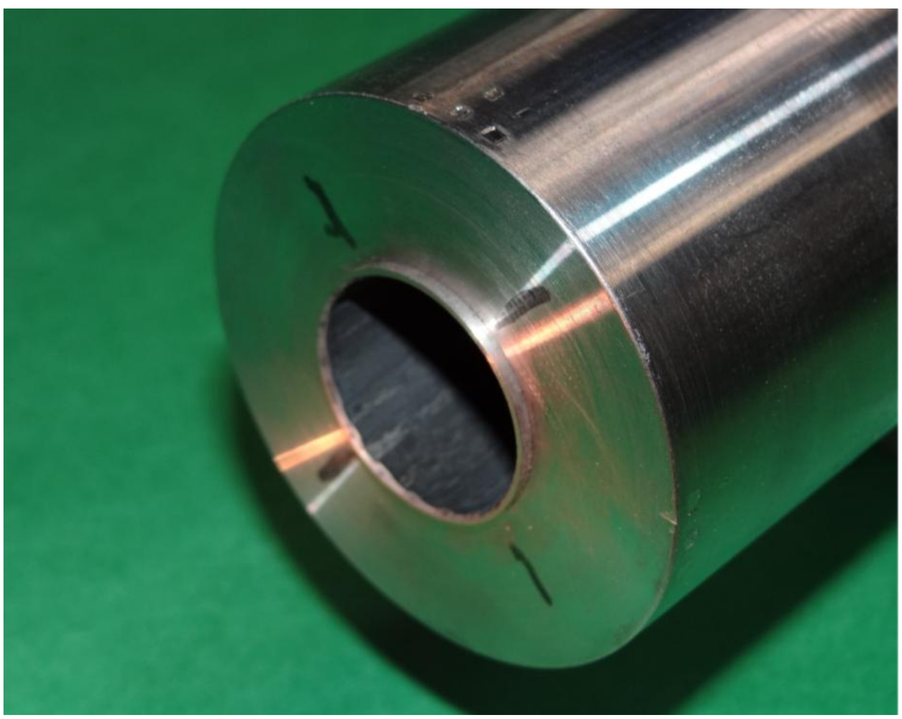

Figure 13. Muzzle end of the third barrel showing liner extension.

6.3 Post Test Investigations

6.3.1 First Barrel

A central portion of the first barrel was removed and sliced into samples suitable for bond strength measurements. Machining was done with an electric discharge machine (EDM). These measurements were made in the manner described in (*3*); table 3 gives the results. The measured bond strengths are approximately one-third of what was expected.

Table 3. Bond strength measurements for first barrel.

Disk Number	**Maximum Load (lb)**	**Disk Thickness (in)**	**Liner Outer Diameter (in)**	**Bond Strength (psi)**
1	742.7	0.199	1.095	1085
2	702	0.194	1.094	1053
3	664	0.197	1.091	983
4	790.3	0.198	1.091	1165
5	834.9	0.198	1.095	1226

The barrel was further sectioned by EDM to reveal the breech end of the liner. The liner fell out during the machining process. The surface underneath where the liner was attached was seen to be much rougher than the machined surface of the liner. After putting the liner back in the gun tube, a short strip of the rough surface was observed. This strip was interpreted to be the distance that the liner was displaced during the firing process. The length was measured to be 0.027 in (.686 mm). Figure 14 shows the surface of the breech end of the liner in the gun tube. The liner has been placed in the tube to show the section of the gun tube that has been revealed by the liner movement. Included is a scale on the right side of the picture showing 1/64 in (0.397 mm) divisions.

Finally, hardness measurements were made on one of the slices used in the bond strength tests. An average hardness of 36.7 HRC was determined from eight measurements, which can be converted to a yield stress of 168 ksi.

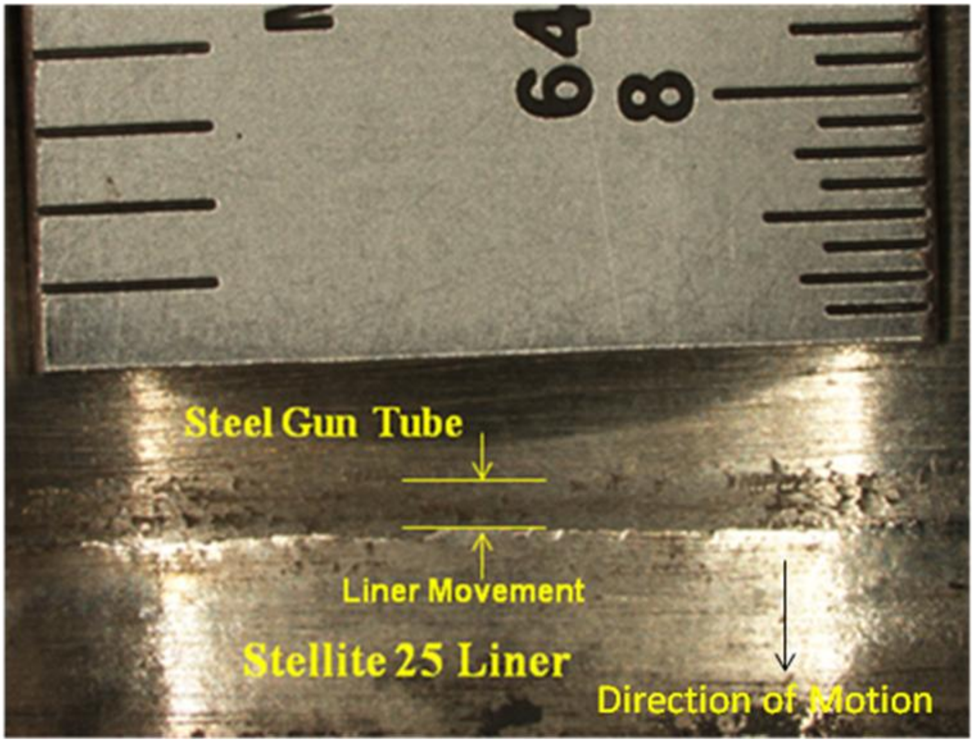

Figure 14. Breech end of Stellite 25 liner inside the first gun barrel.

6.3.2 Third Barrel

Slices were taken from the unfluted section of the third barrel with an EDM machine, and bond strengths were determined in the usual manner. Table 4 gives the results. Again, bond strengths much lower than those achieved with laboratory samples were achieved.

Table 4. Bond strength measurements for third barrel.

Disk Number	Maximum Load (lbf)	Disk Thickness (in)	Liner Outer Diameter (in)	Bond Strength (psi)
1	769.6	0.201	1.090	1118.0
2	716.8	0.202	1.091	1035.3
3	583.4	0.201	1.092	846.1
4	623.7	0.202	1.091	900.8
5	588.4	0.201	1.092	853.3

The breech end of the third barrel was sectioned in a manner similar to that of the first barrel. As before, the liner fell out of the tube in the chamber area when the tube was sectioned parallel to its axis. Figure 15 shows a cross section of the gun tube and liner. The liner has been placed back in the gun tube where it was originally positioned. It is clear that the shoulder in the steel tube and the cold sprayed nickel prevented any motion of the liner. The nickel can be seen as a thin strip bonded to the Stellite 25 liner.

Finally, hardness measurements were made on one of the slices used in the bond strength tests. Average hardness of HRC 35.6 was determined from eight measurements, which can be converted to a yield stress of 163 ksi.

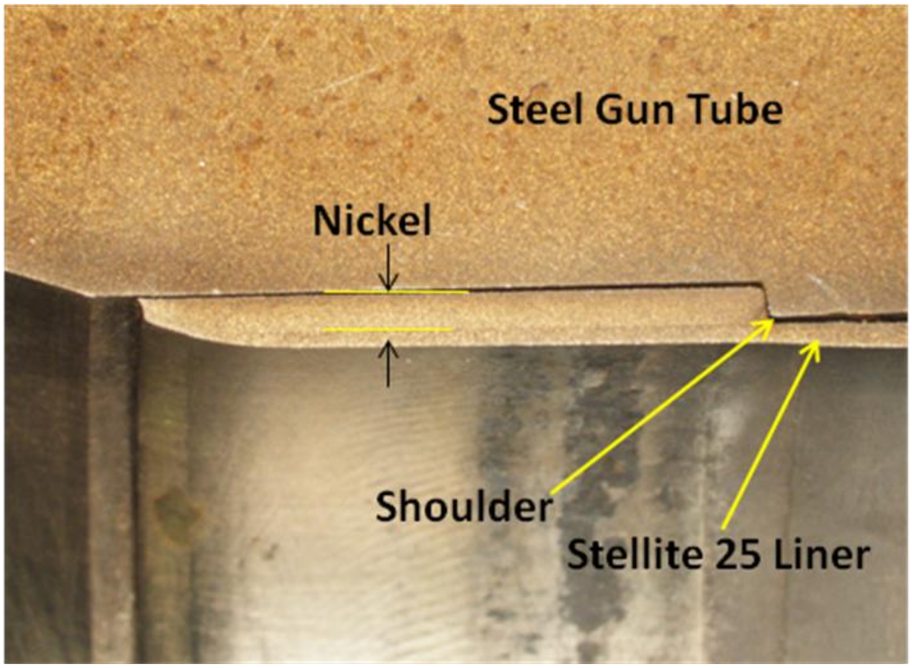

Figure 15. Cross section of liner and gun tube near the breech end of the third barrel.

7. Discussion

The scale-up of the GLEEM process from a laboratory demonstration to an actual gun tube was done on a trial-and-error basis. At the beginning it was not realized how critical it was to keep the gun barrel as vertical as possible. In doing so, the load rod will be aligned with the load axis and keep off-axis forces from deforming it. Systems were in place by the time the third barrel was processed so loads could be uniformly applied for the required length of time. This was not the case with the first tube; the loads were not always maintained for the 30-min hold time.

Bond strengths of the disks sliced from the first barrel were generally higher than those of the third barrel. This is consistent with the somewhat larger liner outer diameters seen in the first barrel. (Compare tables 3 and 4.) However, the bond strengths of both barrels were well below that achieved in the laboratory, which ranged from 2400 to 4500 psi for the laboratory steel tubes with about the same inner and outer diameters (*3*). The liner outer diameter for the third tube after the GLEEM process was only slightly larger than the original outer diameter (1.090 in or 27.69 mm). The outer diameter of the liner should increase by at least 0.2% at a load of 136 kips, according to the development shown in section 4. Had enough plastic deformation been introduced into the gun tube, the frictional bond strength may have been sufficient to keep the liner in place.

The main difference between the laboratory tests and the processing on the M242 barrel is that the elastomer plugs were longer in the case of the M242. This was done to speed the processing time but may have led to increased frictional effects between the elastomer and liner that limited the pressure and hence bond strength. For neither barrel did the inner diameter expansion equal that seen in the laboratory cases, even though the loads on the elastomer were comparable. (Hardness measurements confirmed that the yield strengths of tubes 1 and 3 were comparable to the value used to calculate the required load as shown in section 4.) This suggests that higher loads, combined with shorter lengths of elastomer, are required to achieve comparable bond strengths.

Keeping the unsupported length of the load rod to a minimum was also a crucial aspect of the process. One of the problems encountered when working with a barrel that was already machined is that the push rod must pass through the chamber area at some point. A metal insert that fills the chamber could be made that would support the pusher rod there. This was not done for this work. Processing the tube from the muzzle end first helped to alleviate this problem. If the tube were in the form of a forging with a central bore, then this problem could be avoided.

It was not expected that the liner would extend from the tube, based on the bond strength achieved in laboratory tests. This was assuming that the liner acted as a rigid body. The observations that the liner did extend motivated a re-examination of this assumption. It is quite possible that the liner extension was due to the dynamic nature of the interior ballistic process. Figure 16 portrays how the liner movement might occur. Figure 16a shows the bullet in the chamber before propellant ignition. After ignition, the bullet begins to move down the barrel (figure 16b). Immediately behind the bullet, the gun tube and liner expand slightly due to the pressurized gasses. This may stretch the liner, and it could begin to pull away from where it was seated. The pressure is reduced in figure 16c and the liner and gun tube rebound, moving the liner still further away from its original seated position. Finally, in figure 16d, the pressure in the tube is gone. However, the liner might never return to its original position. In this way, the entire liner does not move at once, so that it does not move as a rigid body. Its motion is not unlike that of a wrinkle moving a rug a small amount as it traverses the length of the rug. In this way, liner extension can be a result of both liner stretching and liner movement.

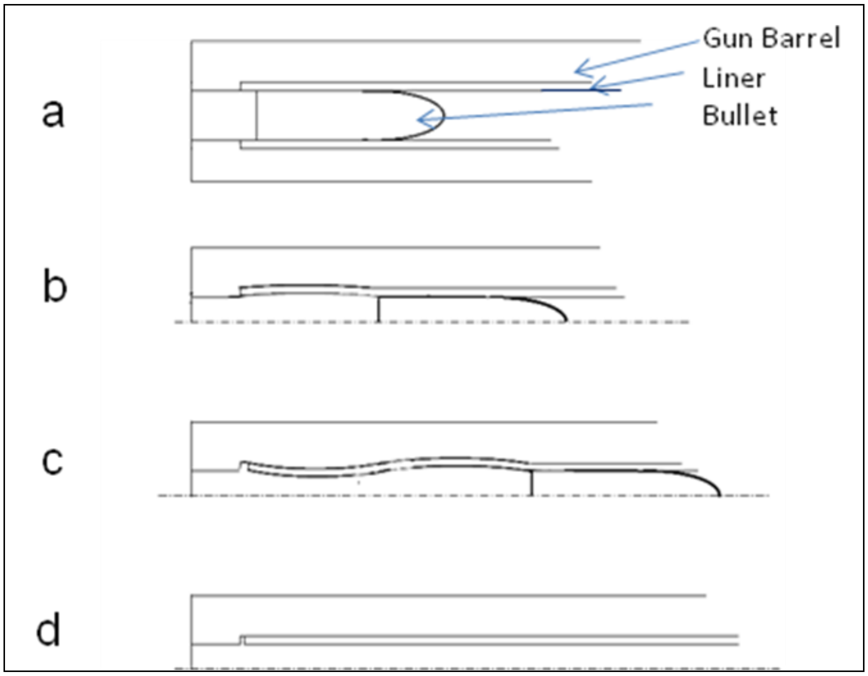

Figure 16. Possible liner motion.

The fact that the total liner extension observed for the first barrel was more than the measured liner displacement at the breech of the gun (0.082 in vs. 0.027 in) suggests that the extension is due to both liner displacement and liner stretching. This hypothesis was supported by the test results for the third barrel. Here, the rear of the liner was pinned in place by the cold-sprayed nickel shoulder. However, a liner extension of 0.062 in after 45 shots was observed. This extension must be due only to liner stretching. On a per-shot basis, the stretching of the liner in the third barrel is much less than that observed for the first barrel (0.0014 in/shot versus 0.0032 in/shot).

No extension has ever been seen with liners that have been explosively bonded to the gun tube. The strength of an explosive bond approaches or is equal to that of a true metallic bond. While the bond strength was sufficiently high in the present work to allow machining of the liner, a higher bond strength than that achieved for the two barrels that were fired is required if liner stretching and liner displacement are to be eliminated.

8. Summary

Stellite 25 liners have been emplaced in three M242 medium caliber cannon barrels with the GLEEM process (Gun Liner Emplacement with an Elastomeric Material). Several lessons were learned in the scale-up of this process from laboratory tubes to an actual gun barrel. A satisfactory process was achieved by the time the third barrel was processed. Liner extension was observed during the firing of the first barrel which led to the attachment of a shoulder on the liner placed in the third tube. Liner extension was also seen in this barrel, although at a much lower rate. Observations of the liner at the breech end of the barrel indicated that the liner extension was due to both liner displacement and liner stretching. An explanation for liner movement was suggested that likened the movement to that of a wrinkle crossing a rug. Push-out tests conducted on the liners revealed that the bond strengths between the liner and fired gun barrels were significantly lower than those achieved in comparable steel cylinders. A possible cause of the lower strengths was the use of longer elastomer rods, leading to higher friction effects and reduced pressure on the gun barrel wall. Pinning the rear of the liner reduced the liner movement. However, higher bond strengths will be required to keep the liner from both stretching and displacing.

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List of Symbols, Abbreviations, and Acronyms

a	radius of gun liner
ARL	U.S. Army Research Laboratory
b	outer radius of gun tube
DIC	digital image correlation
E	elastic modulus
EDM	electro-spark discharge
F_b	buckling load
GLEEM	gun liner emplacement with an elastomeric material
h	load rod radius
HRC	hardness measurement on the Rockwell C scale
I	moment of inertia
K	column effective length parameter
L	applied load
λ	unsupported load rod length
P_i	internal pressure in a gun tube required to cause plastic deformation
RTV	room temperature vulcanization
σ_y	yield strength

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