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Machine Gun Liner Bond Strength

by William S. de Rosset and Jonathan S. Montgomery

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14. ABSTRACT Bond strengths of two Stellite 21 liners in the M2 0.50-cal. machine gun have been measured. Both liners were obtained from machine-gun barrels that had been retired from service. Liner bond strength from one of the barrels was measured to be ~750 psi. The other liner fell out of the barrel during sectioning, and its bond strength was much lower. Simple calculations showed that a bond strength of 750 psi was compatible with a shrink-fit process. In this case, the bond strength was shown to be sufficient to resist the forces on the lands and grooves of the liner due to spin-up forces on the bullet.			
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1. Introduction

The U.S. Army is currently pursuing efforts to reduce gun barrel wear and erosion. These efforts are primarily centered around the work being conducted at Benet Laboratories on coating the bore of large-caliber, smooth-bore gun tubes with tantalum. In addition, there is a program to replace electroplated chrome coatings in medium caliber gun tubes (*1–5*) with a refractory metal liner being conducted jointly by the U.S. Army Research Laboratory (ARL) and Benet Laboratories. This latter program has examined explosive bonding of pure tantalum, several tantalum alloys, and Stellite 25 (an alloy of cobalt, chrome, nickel, and tungsten) in a liner configuration. These metals have been chosen for their high-temperature properties and ability to resist chemical attack.

In addition to resisting chemical attack, Stellite 25 has additional characteristics that make it attractive as a gun barrel liner. First, it is relatively inexpensive as compared to tantalum and its alloys. Second, Stellite 25 has sufficient ductility for it to be explosively bonded to the inner bore of an M242 Bushmaster medium caliber cannon (*4*). Third, Stellite 21, an alloy similar to Stellite 25, has already been in use for over half a century as a liner material for the M2 0.50-cal. machine gun. Fourth, Stellite 25 has a shear strength high enough to resist the reaction forces of the projectile on the lands of the rifled M242 barrel. (It was estimated that pure tantalum would not have a high enough strength to be used in the M242. This was the reason for examining tantalum alloys.) Finally, it is expected that Stellite 25 can be machined to form the lands and grooves of a rifled barrel. (Difficulties have been experienced in machining an explosively-clad tantalum alloy in an M242 Bushmaster barrel [*6*].)

One disadvantage of Stellite 25 was demonstrated by Smith (*7*), who made hot hardness measurements on samples of explosively-bonded Stellite 25. He found that the material strength drops rapidly between 400 and 800 °C. This was a concern as the inner wall temperature of an M242 can exceed 900 °C (Standard Firing Cycle A, 150 shots, bare steel wall [*8*]). Note, however, that if the barrel were lined with a refractory metal liner, the steel portion of the gun barrel would have a lower temperature, depending on the liner thickness. The hot hardness values of both Stellite 21 and Stellite 25 were obtained from the Alloy Digest (*9*) and are compared in figure 1. Unfortunately, Smith's measurements were made on an uncalibrated system and cannot be compared in this figure. This figure shows that there is a rapid drop in the hot hardness of Stellite 25, as evidenced by the drop in the tensile strength between 650 and 800 °C. The hot hardness for Stellite 21 does not undergo a steep drop in the 650–800 °C range. However, it does decrease rapidly in the 800–1000 °C range so that the difference in hot hardness between Stellite 21 and Stellite 25 is not that great in the upper temperature range.

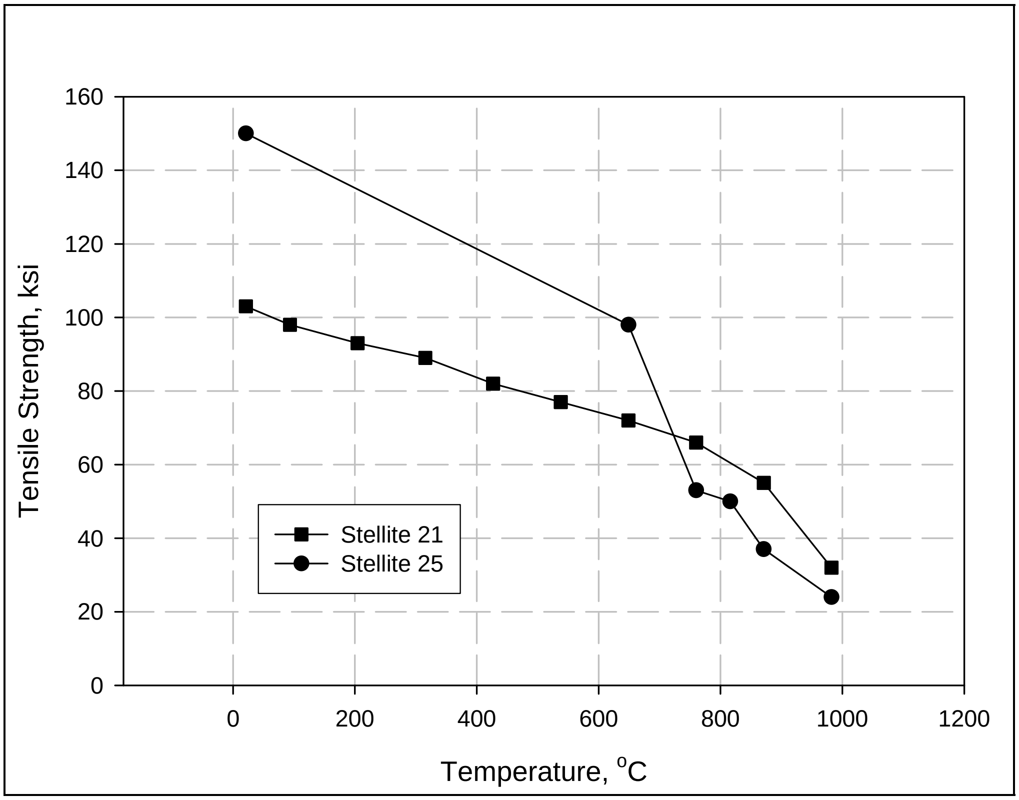

Figure 1. Comparison of hot hardness between Stellite 21 and Stellite 25.

Due to these material properties and processing issues, attention was turned to Stellite 21 as a possible liner material for the M242 Bushmaster automatic cannon. Unfortunately, Stellite 21 does not have sufficient ductility to be explosively bonded, and an alternative means of attaching the liner to the gun barrel must be employed. The primary concern was that the method chosen would provide a high bond strength between the liner and the gun barrel to survive firing. Previous work by Concurrent Technologies Corporation (CTC) (*10*) indicated that using a number of pins to provide a mechanical bond was not sufficiently strong to keep the a tantalum liner in an M2424 gun tube from rotating due to reaction forces of the projectile with the rifling. The method by which the Stellite 21 liner is attached to the M2 machine gun might be applicable for a larger-bore gun; however, this technology is proprietary to the manufacturer and not readily available to the U.S. Government (*11*).

Thus, the decision was made to conduct a limited study of M2 Stellite 21 liners to ascertain how the liners are attached to the gun barrel. Two unserviceable M2 barrels from the U.S. Army Aberdeen Test Center (ATC) were sectioned to reveal the liner configuration. The following section describes the liners from these two barrels and discusses probable reasons for their condemnation. Section 3 discusses and presents results from the bond strength tests. The fourth section discusses estimates of the bond strength necessary to resist the reaction forces of the bullet on the lands and grooves of the liner.

2. Gun Liner Observations

Two unserviceable M2 machine gun barrels were obtained from ATC. Three cuts normal to the length of the barrel were made in the first barrel to isolate the breech end, a small ring, and a 7-in section of the liner. A rough schematic of the cut locations is shown in figure 2.
The parts containing the breech end and the 7 in length of liner were then sectioned along the axis of the barrel by electrical discharge machining (EDM) to reveal the interior surfaces. The 1/2-in ring was retained for bond strength tests.

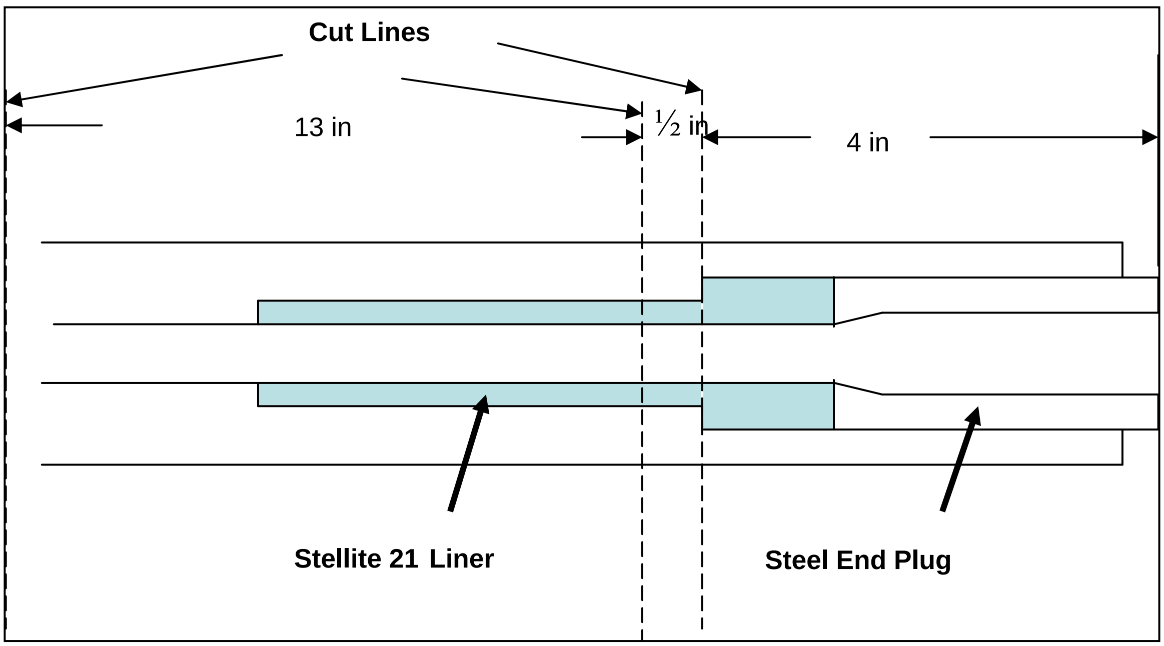

Figure 2. Cut lines in the 0.50-cal. M2 machine gun barrel (not to scale).

Figure 3 shows the interior surface of the breech end of the first machine gun. The sectioning reveals that the liner is slipped into the gun tube and held in place by a steel end plug. When the part containing the 7-in length of liner was sectioned, the liner fell out. A picture of the sectioned liner from this tube is shown in figure 4.

Gun-powder residue was found on the outer surface of the liner. A visual inspection of the lands and grooves showed little or no evidence of any wear. However, at about 1/2 in from the end of the liner (the right end of the liner shown in figure 4) is a small crimp in the liner. It is surmised that propellant gasses got between the liner and gun tube and partially crimped the liner. This failure in the liner may have been the reason for the removal of the gun from service. It was found that the lands and grooves of the liner lined up perfectly with those in the gun tube, indicating that there had been no rotation of the liner inside the gun tube before the tube was sectioned.

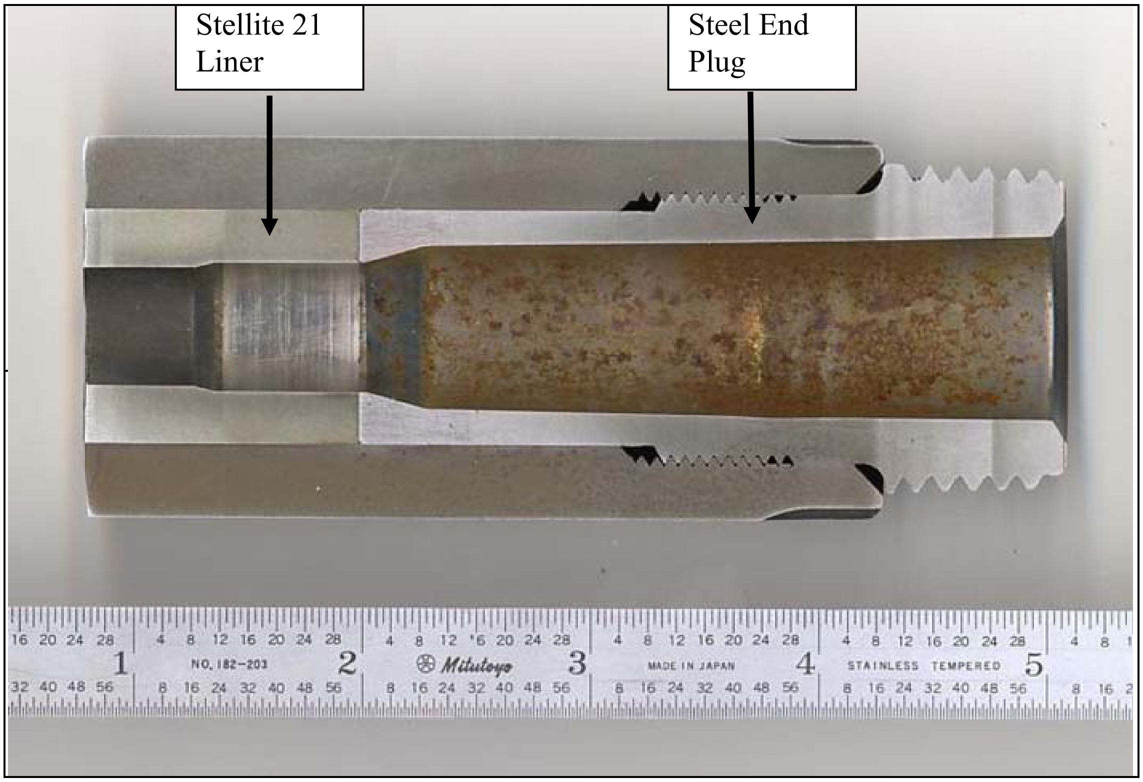

Figure 3. Sectioned breech end of the first 0.50-cal. M2 machine gun barrel.

Figure 4. Stellite 21 liner removed from the first M2 machine gun barrel.

The second gun barrel was sectioned to show the position of the liner step-down in thickness (see figure 5). In this case, the liner remained attached to the tube. A 1.5-in piece was cut from the remaining portion of the gun barrel. This piece was sectioned into five rings and used to determine the bond strength between the liner and gun tube.

The liner in the second barrel showed clear signs of wear. There were obvious pits and cracks occurring in the first three inches of bullet travel. A close-up of this region is shown in figure 6. Two cracks shown in this figure extend from the inner to outer diameter of the liner. Many of the pits are in a line that follow the pattern of the lands and grooves. Even with this extensive liner wear, there is no sign that the propellant gasses have reached the gun barrel inner surface and damaged it. None of the pits is as deep as the liner thickness. This pitting would likely lead to gas blow-by and lack of obturation.

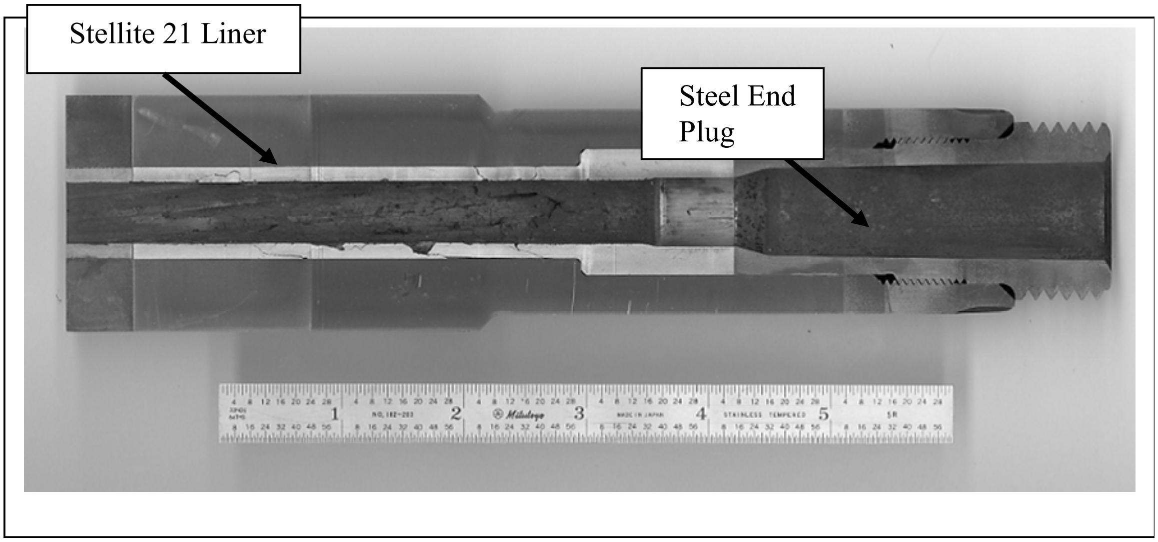

Figure 5. Sectioned sample of the second M2 machine gun barrel.

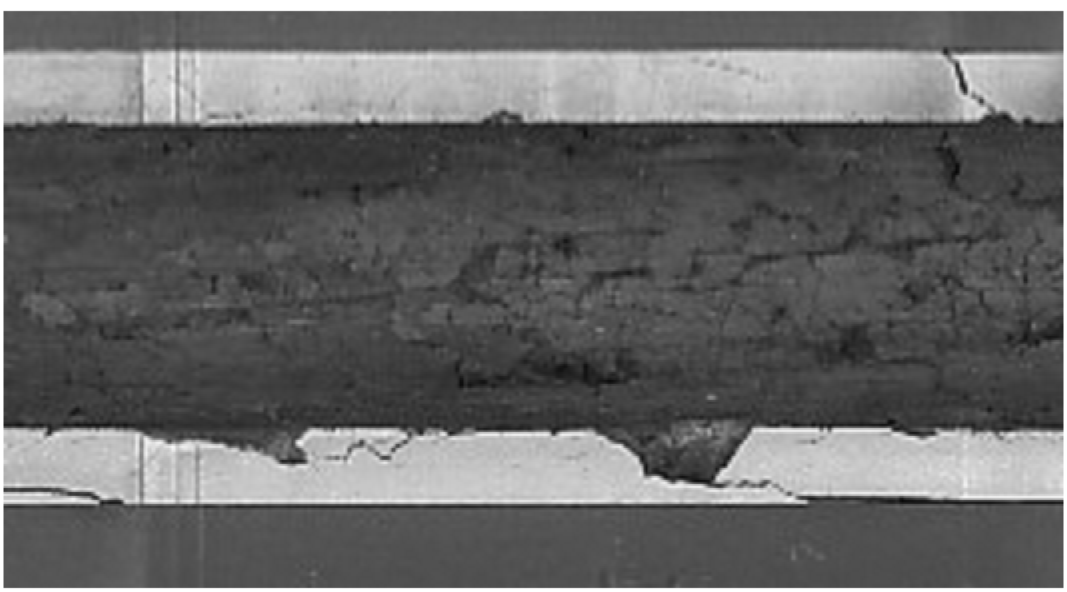

Figure 6. Close-up of worn Stellite 21 liner.

3. Bond Strength Tests

The bond strength of an explosively-formed bond has been measured for liners in the M242 Bushmaster medium-caliber cannon (*5*). The same approach was used to measure the bond strength of the Stellite 21 liner in the M2 machine gun. Seven samples were tested, two from the first gun tube and five from the second. A steel plug was designed so that its shoulder rested on the liner but did not interfere with the steel gun tube inner wall. The dimensions for the plug used in these tests are shown in figure 7. The ring was placed in a fixture that allowed the liner to be displaced from the tube. The ring, test fixture, and plug were placed in an Instron* model 1125 test machine. Load was applied with the crosshead moving at a constant rate of 0.05 in/min until the liner was displaced. Using the load required to displace the liner (F) and the contact area (A), the bond shear strength τ could be calculated using

$$\tau = F / A . \tag{1}$$

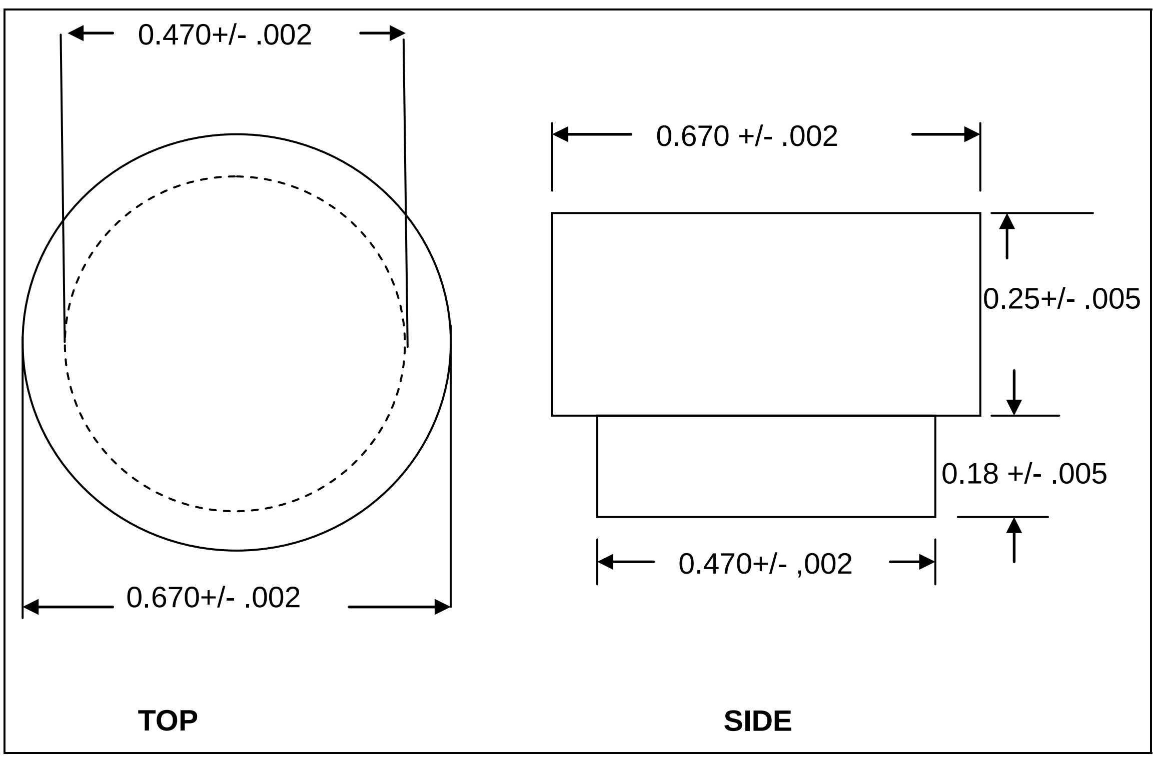

Figure 7. Steel plug design for bond strength tests. All dimensions are in inches.

*Instron is a registered trademark of Instron Corporation, Norwood, MA.

An example of a load-displacement curve is shown in figure 8. The load increases smoothly as elastic stresses increase in the plug and liner. At a certain level of displacement, the load reaches a peak and then drops sharply. The cross-head displacement continues to increase as the load decreases.

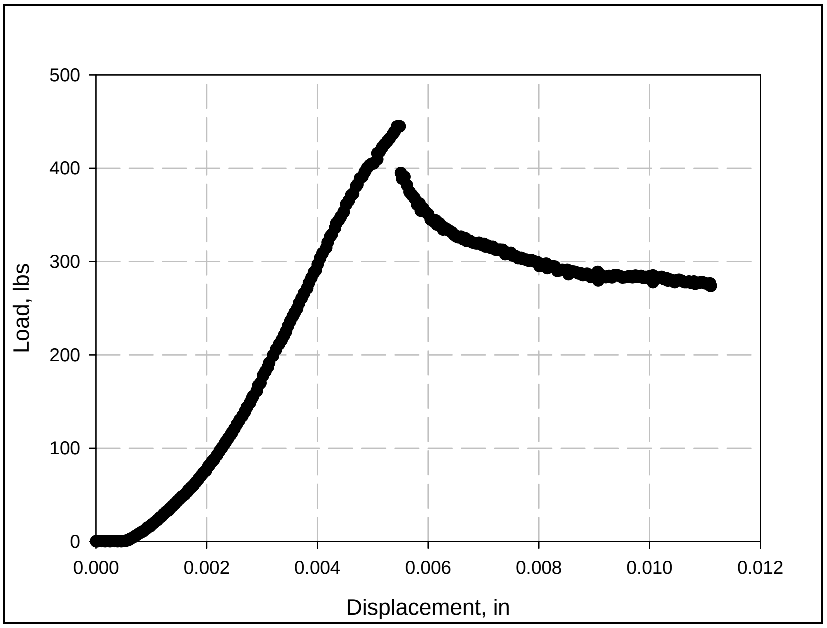

Figure 8. Load-displacement curve for sample MG3.

A summary of the seven tests is shown in table 1. Tests labeled MG-6 and MG-7 are from the first gun barrel. The others are from the second gun barrel. The average bond strength for the second tube was 776 psi with a mean deviation of 86 psi. The bond strength for the first tube was substantially less, consistent with the observation of the liner falling out of the gun tube after sectioning.

Table 1. Experimental bond strength data from two M2 machine gun barrels.

Sample Designation	**Ring Thickness (in)**	**Liner Outer Diameter (in)**	**Maximum Load (lb)**	**Calculated Bond Strength (psi)**
MG1	0.197	0.753	291.0	624
MG2	0.197	0.754	332.5	713
MG3	0.197	0.753	444.8	954
MG4	0.197	0.750	376.9	812
MG5	0.197	0.751	361.1	777
MG6	0.210	0.749	215.2	436
MG7	0.210	0.750	97.6	197

4. Discussion

This limited investigation does not constitute a complete analysis of liner failures in the M2 machine gun. The fact that two different liner-failure modes were seen in the two barrels that were examined is serendipitous. The first barrel liner examined failed most likely due to propellant gas that got between the liner and barrel, crimping the liner and disturbing the passage of the bullet. This failure apparently occurred after very few rounds were fired, as indicated by the low wear on the liner. This type of failure might have been caused by a manufacturing defect and should occur much less often than the second type of failure observed. The liner in the second barrel that was examined failed by the normal erosion process associated with the interior ballistics cycle as evidenced by the numerous pits and cracks.

Both liners exhibited low bond strength. The bond was virtually non-existent for the first tube examined, possibly due to the manufacturing defect. The bond determined for the second liner is likely to be more typical of what a proper manufacturing process would achieve. The average bond strength determined in this case is still much less than that achieved through explosive bonding. Compare the average of 776-psi bond strength for the machine gun liner vs. a bond strength in excess of 45 ksi for an explosively-formed bond (*5*).

4.1 Shrink-Fit Calculations

The low bond strength suggests that a shrink-fit process may have been used to join the two parts. An order-of-magnitude estimate can be made of the bond strength in this case using a standard elastic analysis and some reasonable assumptions. The first assumption is that the steel barrel can be heated to 350 °C and the liner cooled with dry ice to –78.5 °C without affecting their material properties. The gun tube will expand, and the liner will shrink according to their respective coefficients of thermal expansion. These are taken to be 14 μ-in/in-°C and 16 μ-in/in-°C for the Stellite 21 and steel, respectively.

In the conditioned state, the clearance between the liner and gun tube should be at least 0.002 in on the radius. The gun tube bore diameter was measured to be 0.75 in. For a Stellite 21 liner with an outer diameter of 0.751 in, the temperature differential will provide a difference of 0.004 in on the diameter. This difference in radial dimensions produces a residual stress after cooling. The pressure P at the interface between the liner and gun tube can be calculated by

$$P = (E\delta / b)\frac{(b^2 - a^2)(c^2 - b^2)}{2b^2(c^2 - a^2)}, \qquad (2)$$

where

E = average modulus	= 32000 ksi
a = inner radius of liner	= 0.25 in
b = interface radius	= 0.375 in
c = outer radius of the gun tube	= .9625 in
δ = interference	= .001 in.

We have chosen to use a modulus that is an approximate average of those of the steel and Stellite 21 in order to simplify the calculations. Given these values, P = 21 ksi. The pressure can be converted into a shear strength of the bond through the coefficient of static friction. Since this value can range from 0 to 1, the maximum shear strength that can be attained is 21 ksi. This is clearly much larger than the bond strengths that were measured and would indicate a very low coefficient of static friction if, indeed, the liner were emplaced with a shrink-fit process using the parameters shown above. More likely, the liner was emplaced simply by press-fitting it into the barrel.

From a manufacturing standpoint, using the shrink-fit process to attach a Stellite 21 liner to a Bushmaster medium-caliber cannon may not be feasible. The length of liner needed is much greater, ~6 ft in contrast to the 8 in needed for the M2, and the tolerances on the dimensions would be much more difficult to meet.

4.2 Bond Strength Requirements

The bond strength of the Stellite 21 liner in the M2 machine gun is small but must be sufficiently high to overcome the reactive force that imparts spin to the bullet. An order of magnitude estimate of this force can be made with a few simplifying assumptions. First, assume that the bullet undergoes constant acceleration down the gun tube. The M2 tube length is 44.875 in (1.139 m), and the muzzle velocity is 930 m/s. With constant acceleration a,

$$D = v^2 / 2a \, , \tag{3}$$

where D is the bullet travel and v is its velocity. Using the tube length for D and the muzzle velocity for v, we get

$$a = 3.8{*}10^5 \text{ m/s}^2 \, . \tag{4}$$

The twist of the rifling was measured to be 13.75 in (0.349 m) for each complete rotation. Thus, the distance the bullet travels is related to its angular orientation by

$$D = (0.349/(2\pi))\Theta \, , \tag{5}$$

where θ is the bullet's angular orientation (in radians). Successive differentiation leads to

$$a = (0.349/(2\pi)) \, d\omega/dt \, , \tag{6}$$

where ω is the bullet rotation rate. The torque T on the bullet is given by

$$T = I\, d\omega/dt\ , \tag{7}$$

where I is the moment of inertia. If we approximate I by

$$I = \tfrac{1}{2} MR^2\ , \tag{8}$$

where M is the bullet mass (0.046 kg) and R is the bullet radius (0.00635 m), then

$$T = ½*(0.046)*(0.00635)^2* (3.8*10^5)*(2\pi/0.349) = 6.3 \text{ N·m}\ . \tag{9}$$

The force F on the liner is then given by

$$F = T / R'\ , \tag{10}$$

where R' is the outer radius of the liner (0.375 in or 0.00952 m).

This force is absorbed by the bond between the liner and gun tube. The liner length is ~9 in (0.228 m). Thus, the area A of this bond is given by

$$A = 0.228*2*3.14*0.00952 = 0.0136 \text{ m}^2. \tag{11}$$

Finally, the shear stress σ on the liner is given by

$$\sigma = F/A = 0.049 \text{ MPa} \sim 7 \text{ psi}. \tag{12}$$

This value is significantly lower than the bond strength that was measured on the two barrels. The calculation also offers some insight as to why the approach CTC used to fasten the liner to the gun tube failed. The stress on the liner was primarily concentrated at the mechanical pins rather than being spread out over a bonded surface. In addition, the projectile was more massive and the bore diameter was larger. The concentrated stress was able to overcome the strength of the mechanical fasteners.

5. Summary

The use of Stellite 21 as a liner material for medium caliber gun tubes has been considered. In order to learn more about how Stellite liners might be attached to these gun tubes, two 0.50-cal. machine-gun barrels were obtained from ATC. These barrels have been sectioned with the aim of determining the state of the Stellite 21 liner as well as the bond strength between it and the gun barrel. Two modes of liner failure were observed. In the first, propellant gasses at the end of the liner nearer the muzzle separated the liner from the barrel.

There was very little observed wear on the lands and grooves of this liner. The liner from the second gun tube showed extensive wear and cracking. The bond strength of one of the liners was measured to be ~750 psi. This bond strength is possible to achieve with a shrink-fit process. However, the magnitude of the calculated interface pressure resulting from a possible shrink-fit process was much higher than that actually measured, indicating that the liner emplacement may have been accomplished with a press-fit operation. While a shrink-fit process could be used for the short liner found in the M2 machine gun, it would be difficult to use it to emplace a Stellite liner in a long M242 Bushmaster barrel. Using a simple analysis of the forces on the machine gun bullet, it was found that the measured bond strength was adequate to resist the reaction forces produced when the bullet was spun up. Thus, the high bond strengths achieved through either explosive bonding or a shrink-fit process are not required.

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