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# Fabrication and Tests of M240 Machine Gun Barrels Lined with Stellite 25

by William S de Rosset and Sean Fudger

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# **Fabrication and Tests of M240 Machine Gun Barrels Lined with Stellite 25**

**by William S de Rosset and Sean Fudger**  
*Weapons and Materials Research Directorate, ARL*

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## **Acknowledgments**

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## 1. Introduction

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For the past several years, the US Army Research Laboratory (ARL) has been developing a process by which refractory metal liners can be attached to steel gun barrels.<sup>1-6</sup> This process, known as Gun Liner Emplacement with an Elastomeric Material (GLEEM) has been used, along with hammer forging, to emplace niobium liners in M240 machine gun barrels.<sup>7</sup> The combination of GLEEM and hammer forging produced a composite barrel whose liner stayed in place during an aggressive firing schedule. However, the niobium liner experienced a significant amount of wear. Consequently, a search for a more robust refractory metal liner was undertaken.

Cobalt-chromium alloys have shown great promise as liner materials in recent work.<sup>8,9</sup> Unfortunately, there are no commercially available tubes made from these alloys in the specific sizes that were required. At first it was decided to use the cold-spray process to fabricate tubes made of Biodur\* in-house at ARL. These efforts were not successful, and the problems encountered with this work are described in Appendix A.

The cobalt-chromium alloy Stellite 25 was next considered. This decision was based, to some extent, on the successful use of this material as a liner in the M240 machine gun.<sup>10</sup> The approach taken by the US Armament Research, Development and Engineering Center (ARDEC) was to have the entire length of the gun tube made from Stellite 25 (also known as L605). The inner core of Stellite 25 was surrounded by a steel jacket. The liners were made by the flow-form process at ATI Flowform Products, Billerica, Massachusetts. ARL contracted this company to make 5 Stellite 25 liners with the following dimensions: 22-inches-long, 0.312-inches inner diameter, and 0.434-inches outer diameter. These were the same dimensions used with the niobium liners. Figure 1 shows a Stellite 25 liner next to a steel barrel blank.

The specific details of how the liners are flow-formed are proprietary to ATI. However, the general process can be described as follows. First, a preform of the desired material is made in a cylindrical shape with a hole down the center. The preform is placed over a mandrel, and 3 external wheels apply pressure to the preform as they rotate around the preform and move along its length. This results in plastic deformation of the preform into a longer, thinner piece. The part is then stress relieved, and the process is repeated until a near net shape is achieved.

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\*Biodur is a cobalt-chromium-molybdenum alloy made by Carpenter Technology, Reading, Pennsylvania. Its main use is for medical implants.



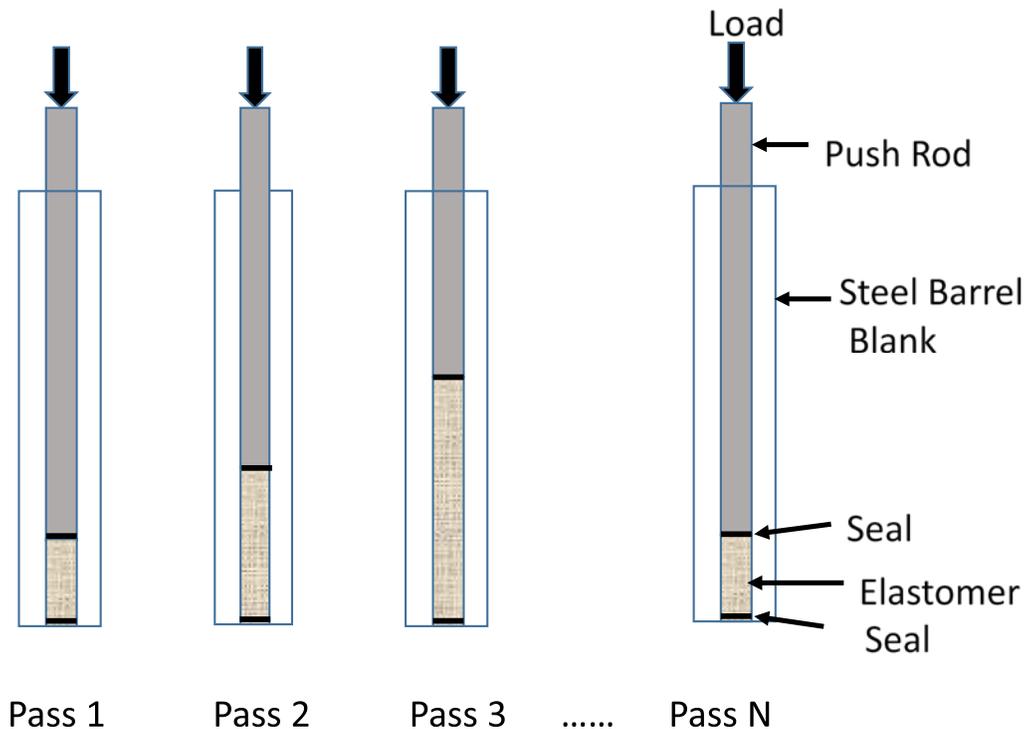
**Fig. 1** Picture of a Stellite 25 liner and a steel barrel blank. The liner has been sprayed with a thin layer of tungsten carbide particles.

Subsequent machining produces the final dimensions. In the case of the tubes made for ARL, a final stress relief was performed to make them amenable to the GLEEM process. The cost for the preform design, tooling, and engineering drawing package can be substantial, but once those costs are covered, additional parts can be made at a relatively low cost.

## **2. GLEEM Processing Parameters**

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The GLEEM process is shown schematically in Fig. 2. Several passes are needed to complete the process because friction between the elastomer (EL) and liner prevents the load from being evenly distributed along the length of the EL. Each pass has an increased EL length and a decreased push rod (PR) length. The number of passes is dictated by the length of the liner. The EL increases in length approximately several liner diameters for each pass.



**Fig. 2 Schematic of GLEEM process**

After a certain number of passes are completed, the composite barrel is flipped over, and the process starts at the other end of the tube. This is shown as “Pass N” in Fig. 2.

There are 2 factors that must be considered in determining the length of the PR. First, it must be long enough so that the load machine does not bottom out on the top of the steel barrel. The EL is compressed a different amount on each pass, so the displacement of the rod varies from pass to pass. Second, the rod’s length needs to be minimized to avoid buckling the portion of the PR not supported by the liner. In addition, there was a constraint on the applied load: it must not produce a stress that is greater than the yield strength of the rod material. In this case, the maximum safe load was determined to be 14,000 lbs. This was the same load that was used to process the niobium liners.<sup>7</sup> A picture of the test fixture is shown in Fig. 3.



**Fig. 3 Test fixture used in the GLEEM process**

Data were previously gathered on the displacement of the PR as a function of EL length plus the seals for the niobium liner processing. Displacements for the first 8 inches of plastic material are shown in Fig. 4. The startup process involved setting the seals and a varying outer diameter of the steel barrel blank. Therefore, a separate least-squares-fit (to the data) for plastic lengths of less than 8 inches was made. The result was

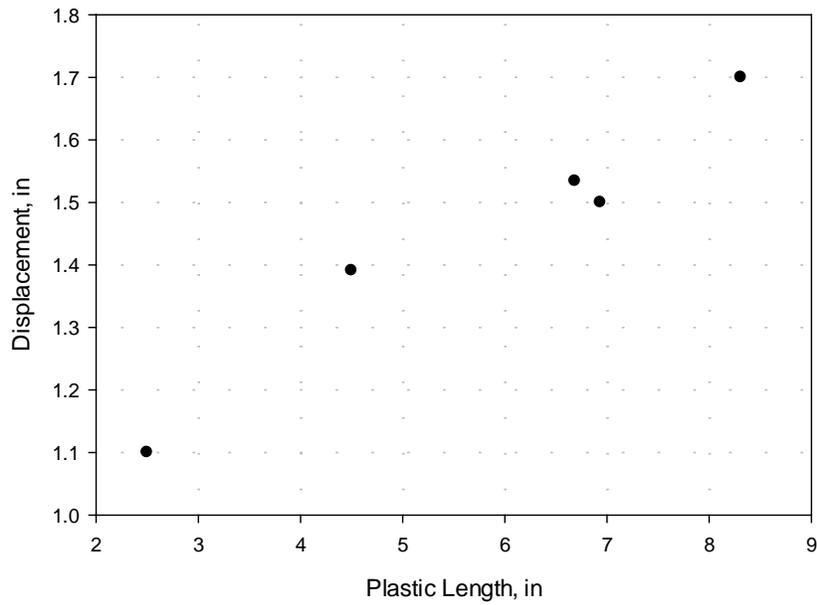
$$D = 0.0949*PL + 0.8956, PL < 8, \quad (1)$$

where D is the load machine displacement and PL is the length of the EL and seals in inches.

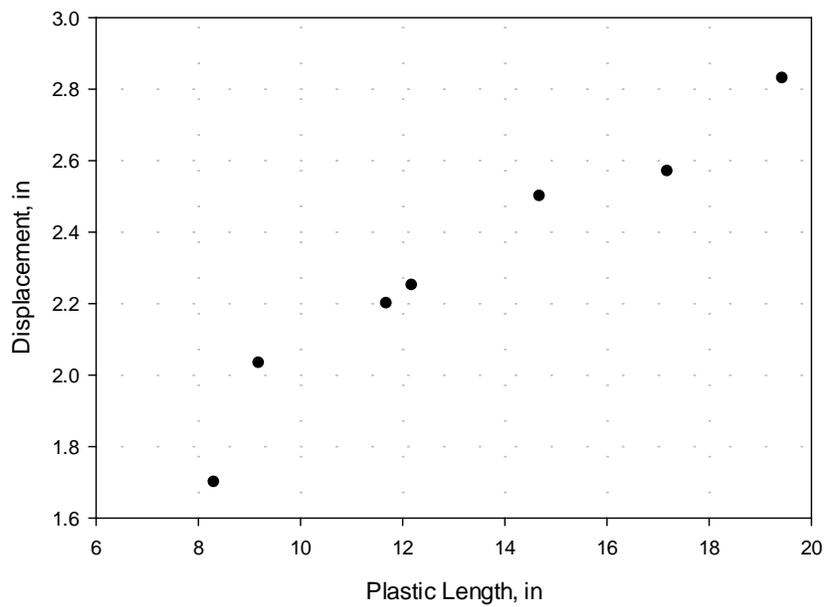
A similar plot was made for lengths greater than 8 inches. This is shown in Fig. 5. A least-squares- fit to the data gives

$$D = 0.0886*PL + 1.1248, PL > 8. \quad (2)$$

In actual practice, steel PRs were machined to various lengths. It was then a matter of calculating the length of EL needed for each load that produced a final clearance between the load frame and the top of the steel barrel blank of 0.5 inches. The EL used was Teflon.



**Fig. 4 PR displacement as a function of plastic lengths <8 inches**



**Fig. 5 PR displacement as a function of plastic lengths >8 inches**

As part of the test fixture, there is a steel centering cup that is placed over the top of the PR. This acts as a pin on the rod and increases the critical buckling length. The PR sits 0.5 inches inside the cup. There is also a 0.5-inch-thick plate covering the top of the steel barrel blank. These parts of the test fixture must be considered when calculating the plastic length.

The combination of PR and plastic lengths must be equal in length to the barrel blank (22 inch), cover plate thickness (0.5 inch), cup intrusion (0.5 inch), and the space between the cup and barrel blank (0.5 inch) at the end of each pass. The 0.5 inch between the cup and barrel blank is arbitrary to some extent. It allows a small safety factor in case a seal is broken and also ensures that the unsupported length is small.

Several relationships are obvious. First, the final plastic length (FPL) after the load is applied is given by

$$FPL = PL - D. \quad (3)$$

Given a final clearance between the top plate and centering cup as 0.5 inches, we have

$$FPL = 23.5 - PR, \quad (4)$$

where PR is the chosen steel PR length. From Eqs. 3 and 4 and for PL less than 8 inches,

$$PL = 23.5 + D - PR = 23.5 + 0.0949 * PL + 0.8956 - PR. \quad (5)$$

Solving for PL, we get

$$PL = (24.3956 - PR)/0.9051. \quad (6)$$

Similarly, for PL greater than 8 inches, we get

$$PL = (24.6248 - PR)/0.9114. \quad (7)$$

Therefore, for any given value of PR, a value of the initial plastic length can be determined. Subtracting the length of the seals (0.75 inch) from this value gives the length of EL needed. Table 1 gives the initially selected PR lengths and the associated length of elastomeric material.

**Table 1 PR and associated EL lengths**

<b>PR (inches)</b>	<b>EL (inches)</b>
22.5	1.34
21.5	2.45
20.5	3.55
19.0	5.21
17.5	6.87
16.0	8.71
15.0	9.81
13.0	12.0
11.5	13.65
9.0	16.39
7.0	18.59

Eventually the barrel is flipped upside down, and the process is continued with decreasing plastic lengths. The actual processing parameters are shown in Appendix B.

As the processing progressed, both the upper and lower seals lost mass. A small part of the upper seal escaped past the PR during each pass and the lower seal was extruded into a small cavity at the base of the barrel. In addition, the pieces of Teflon that were used decreased in length and increased in diameter to accommodate the larger inner diameter of the liner. Therefore, adjustments had to be made to the values of EL as the processing was carried out. These adjustments were minor and are reflected in the numbers in Appendix B.

Before the liners were inserted into the barrel blanks, they were cold-sprayed with a thin layer (~0.0005 inch) of tungsten carbide particles. This was the same procedure previously used with the one niobium-lined barrel that was successfully held in place during high rates of fire.

The Stellite-lined barrel blanks were sent to FN Manufacturing, Columbia, South Carolina. At the facility, the barrel blanks were hammer-forged and machined into the final M240B configuration (complete with handle, flash suppressor, and other hardware). Some machining difficulties were experienced with the niobium-lined barrels<sup>7</sup> that were processed in the same manner. This was not the case with the Stellite-lined barrels and 2 useable gun barrels, which were provided to ARL. Unfortunately, the identity of each barrel was lost in the machining process.

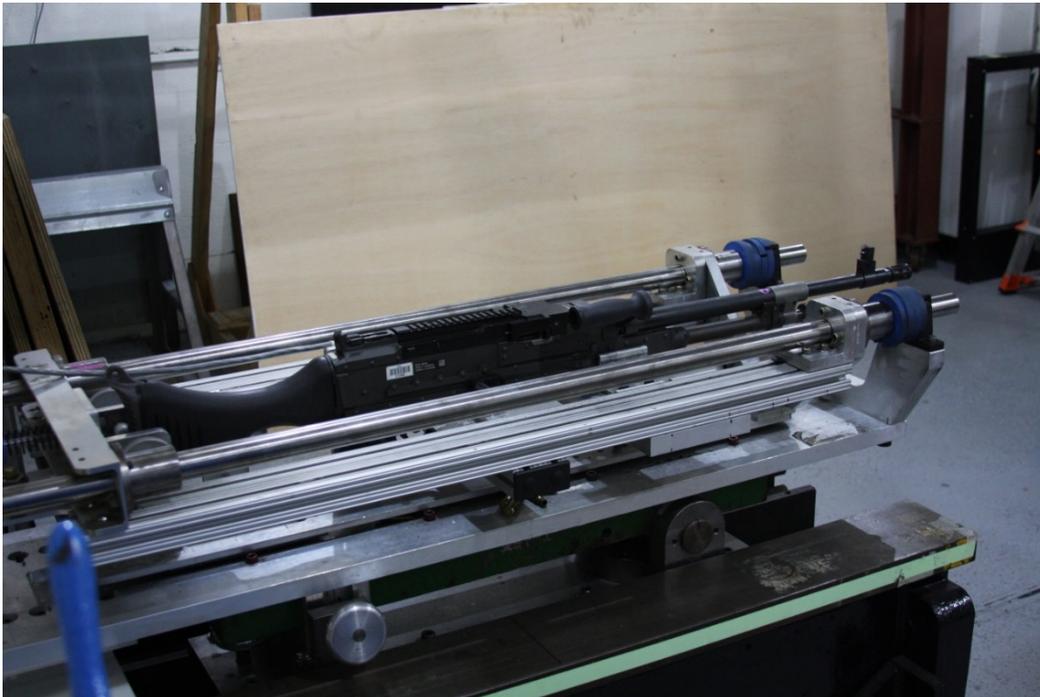
Consequently, the effect of any differences in processing the 2 barrels on the firing results was lost.

### **3. Firing Test Results**

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Firing tests of the 2 barrels were carried out at ARL. The primary goal of the tests was to determine if the liner stayed in place during slow-rate firing. In addition, dispersion and velocity data were collected. The tests were identical to those conducted for the niobium-lined barrels.

A picture of the M240B machine gun in the firing mount is shown in Fig. 6. This mount affords a small amount of recoil for the machine gun. Note that the weapon was fired without the muzzle break.



**Fig. 6 M240B machine gun in firing mount**

The test plan called for 100 rounds of standard M80 ball ammunition to be fired through each barrel. There were 10 warm-up shots and then 3 groups of 30 rounds fired for dispersion and velocity. After each group of rounds was fired, measurements of the liner protrusion from the barrel were made. No liner movement was observed for either barrel after the 100-round test.

The dispersion results are shown in Table 2. The “X” values represent the horizontal dispersion, and the “Y” values represent the vertical direction. During the first set of 30 shots with Barrel 1, it was suspected that the barrel handle was not tight enough.

**Table 2 Dispersion results**

Group no.	Dispersion (mils)			
	Barrel 1		Barrel 2	
...	X	Y	X	Y
1	0.61	0.47	0.39	0.37
2	0.31	0.36	0.01	0.59
3	0.28	0.33	0.20	0.27

For this possible reason, a rather large dispersion was observed. In subsequent tests, the range crew made sure that the barrel handle was tightened for each shot, resulting in a much lower dispersion (~0.5 mils vs. ~0.3 mils).

The average velocities for the 2 barrels are shown in Table 3.

**Table 3 Average velocities**

Group no.	Average velocity (ft/s)	
	Barrel 1	Barrel 2
1	2764	2781
2	2761	2791
3	2764	2788

## 4. Discussion

Two machine gun barrel blanks have been processed with GLEEM and hammer forging. The slow-rate firing tests are considered to be successful because no liner movement was observed. The liner material, Stellite 25, is the second refractory metal that has been successfully shown to be amenable to the GLEEM and hammer-forging process. As long as the liner material can be formed and machined, it is suitable for this process. That opens the possibility for a number of other choices, including niobium alloys that have the strength to resist erosion of the lands in a rifled gun tube.

While it cannot be concluded that spraying the liner with tungsten carbide particles before applying the GLEEM process helped to prevent liner movement, it is probably a prudent measure. Not spraying one of the niobium liners<sup>7</sup> resulted in some liner slippage during firing.

Losing the identity of the 2 barrels during the machining process does not seem to be a problem. It is surmised that the differences in processing were not large enough to have any effect on the firing results.

The slow-rate firing tests need to be followed by high rate-of-fire endurance tests to fully validate the GLEEM/hammer-forging process. Since Stellite 25 has already been demonstrated to have good wear properties as a liner material, the only issue is whether the liner will stay in place when stressed at high temperatures.

## **5. Conclusions**

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Initial firing results showed that the GLEEM process and hammer forging can successfully attach a Stellite 25 liner to an M240B machine gun barrel. This combined process offers the potential to investigate other materials that can be formed and machined into liners.

## 6. References

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1. Carter RH, de Rosset WS, Gray DM. GLEEM – a new composite gun tube processing technology. In: Proceedings of the 26th Annual Army Science Conference; 2008 Dec 1–5; Orlando, FL.
2. de Rosset WS. Gun liner emplacement with an elastomeric material. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2010 Apr. Report No.: ARL-CR-645.
3. de Rosset WS. Gun liner emplacement. In: Proceedings of Gun Tube Conference 2011; 2011 April 11 – 13; Cranfield University, Shrivenham, UK.
4. de Rosset WS. Gun liner emplacement. Journal of Pressure Vessel Technology. 2012;134(4):41009-1–41009-5.
5. de Rosset WS, Gray DM. Refractory metal liner processing for M242 medium caliber barrels. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2013 Jan. Report No.: ARL-TR-6301.
6. de Rosset WS, Gray DM. Processing of niobium-lined M240 machine gun barrels. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2014 Nov. Report No.: ARL-TR-7144.
7. de Rosset WS. Processing of composite gun tubes with GLEEM and hammer forging. Materials and Manufacturing Processes. 2015;DOI: 10.1080/10426914.2015.1026352:1–6.
8. de Rosset WS, Montgomery JS. Cobalt-base alloy gun barrel study. Wear. 2014;316:119–123.
9. Leto EL, Klimm BD, Hespos MR, Garron RF. Flowformed Cobalt Alloy Barrel Testing on the M240 Machine Gun. Picatinny Arsenal (NJ); Armament Research Development and Engineering Center (US); 2014 Aug. Report No.: ARWSE-TR-13013.
10. de Rosset WS, Montgomery JS. Advanced materials gun tube wear. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2012 Apr. Report No.: ARL-TR-5986.

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## **Appendix A. Gun Liner Fabrication**

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Biodur CCM is a cobalt chromium alloy made by Carpenter Technology (CarTech), Reading, Pennsylvania. Its normal composition is given in Table A-1. It gets its name from the fact that it is used in the medical implant industry. The CCM in the name stands for Co, Cr, and Mo. The alloy will hereafter be referred to as Biodur.

**Table A-1 Biodur CCM composition**

<b>Element</b>	<b>Percentage</b>
Co	62
Cr	26–30
Mo	5–7
Fe	≤0.75
Mn	≤0.10
Ni	<1.0
N	<0.25
Si	<1.0
C	≤0.10

Cobalt-chromium alloys have shown great potential for use as gun barrel liners, as demonstrated in recent work.<sup>1</sup> The supposition was that since Biodur was a cobalt-chromium alloy, it would also serve well as a liner material. The plan was to procure Biodur powder and have the tubes made through the cold-spray process. However, it was determined that the carbon content of Biodur was too high and negotiations began with CarTech to make a special research-size batch of Biodur powder with carbon content less than 0.05%. The reason for the low carbon content was that standard BioDur was harder than what was required for a gun barrel liner; reducing the carbon content would make the new alloy more machineable. The plan was to cold-spray the special powder into tubes to be used in the GLEEM process to line gun tubes.<sup>2,3</sup>

CarTech was first contacted in October 2011, but it took 6 months of discussion with CarTech’s sales representative before a final quote for the powder was obtained. The final composition had a carbon content of less than 0.02% and a nominal Cr content of 30%. The price for the research-size batch (~40 lbs) was \$9,238.00. The average powder particle size was 30 microns (as stated in an email on 4 January 2012 from J Hunter, CarTech sales representation). In later

<sup>1</sup> de Rosset WS, Montgomery JS. Advanced materials gun tube wear. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2012 Apr. Report No.: ARL-TR-5986.

<sup>2</sup> Carter RH, de Rosset WS, Gray DM. GLEEM – a new composite gun tube processing technology. In: Proceedings of the 26th Annual Army Science Conference; 2008 Dec 1–5; Orlando, FL.

<sup>3</sup> de Rosset WS. Gun liner emplacement with an elastomeric material. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2010 Apr. Report No.: ARL-CR-645.

discussions with CarTech's technical representative, CarTech's alloy Micro Melt Biodur CCM-LS was determined to meet the carbon content criterion and was selected for the procurement action (telephone conversation, 4 January 2012, Joe Stravinkas, CarTech technical representative). The price for this alloy would not change from the original estimate. (The Cr content for this material was nominally 27.4%, a slight decrease from the 30% requested.)

Procurement action was started for this powder in April 2012, but by July there appeared to be some issues on the part of CarTech in meeting the carbon content specification. CarTech did not supply a cost for the powder to the US Army Research Laboratory (ARL) Contracts Office. It was decided to use the original quote provided by CarTech for the procurement action. After other administrative hurdles were overcome (out-of-date Cage code, signing of the ozone depletion document, etc.), an award was made in June 2013.

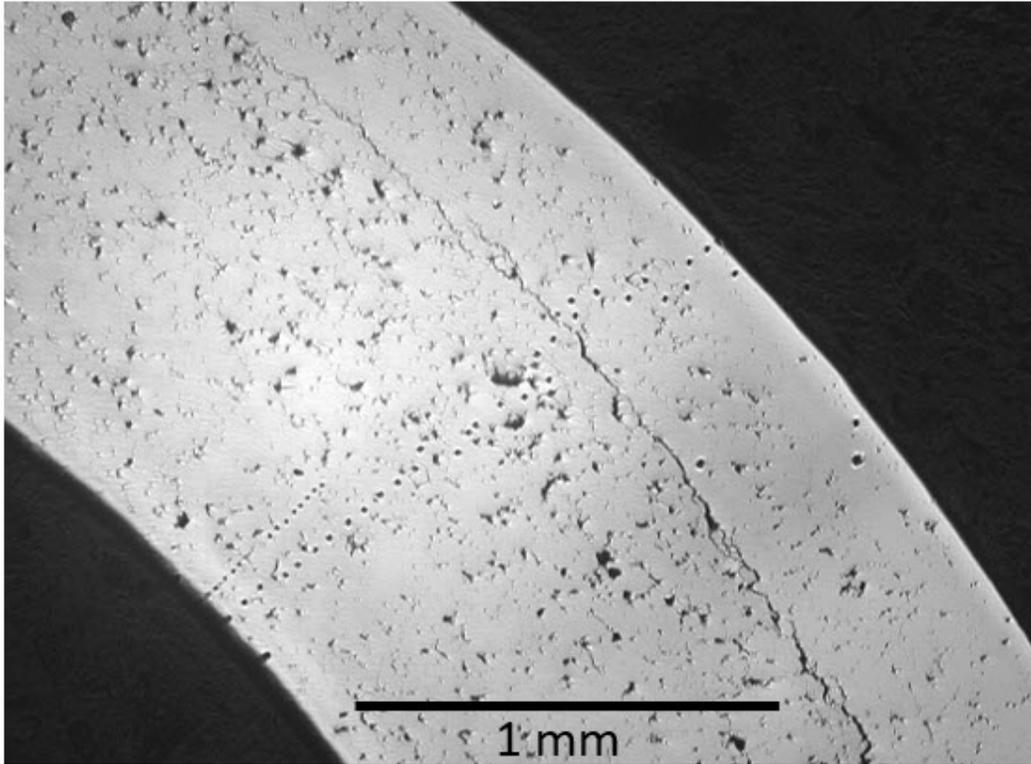
CarTech was contacted in July 2013 to determine how long they would take to make the powder. The reply was that the powder had already been made in anticipation of the order. However, it took CarTech until September to ship the powder.

Arrangements were made to have the powder cold-sprayed into gun tube liners at ARL. The final desired dimensions of the liner were 22-inches-long with an inner diameter of 0.315 inches and an outer diameter of 0.434 inches. These were the same dimensions used in applying the Gun Liner Emplacement with an Elastomeric Material (GLEEM) process to niobium tubes.<sup>4</sup> The strategy used by the ARL cold-spray team was to make an oversized tube that could be machined to the final dimensions.

Difficulties were experienced spraying the tubes. The spray nozzle clogged repeatedly, and the process had to be stopped numerous times to clean the nozzle. In October 2013 one tube was completed and sent to the ARL machine shop for final machining. Unfortunately, the tube cracked before the machining was completed. A 10-inch tube was salvaged from this effort for further studies. Figure A-1 is a micrograph of a cross section of the salvaged tube. There is some porosity observed, as well as a circumferential crack.

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<sup>4</sup> de Rosset WS, Gray DM. Processing of niobium-lined M240 machine gun barrels. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2014 Nov. Report No.: ARL-TR-7144.



**Fig. A-1** Cross section of a Biodur tube that has been fabricated through the cold-spray process. Some porosity was observed, as well as a circumferential crack. Small indentations are due to hardness measurements.

Some of the poor material properties for the Biodur tube could be ascribed to the clogging of the nozzle used in the cold-spray process. Consequently, further effort was made to develop a nozzle that would not clog. This was finally accomplished, and 2 new Biodur tubes were completed in Fall 2014. The new nozzle design is the subject of a patent disclosure.

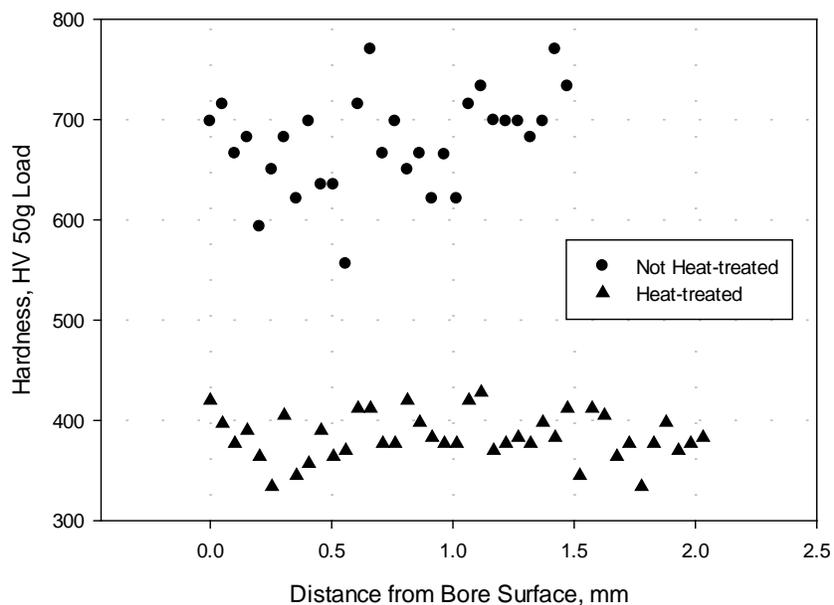
Another source of the poor material properties of the cold-sprayed Biodur tubes was the fact that they were not heat-treated before machining. Solar Atmospheres was contracted to heat-treat the tubes, since there were no furnaces at ARL that were large enough to accommodate the 22-inch-long tubes in a vertical direction. The tubes were shipped to Solar Furnaces in late October 2014. One of the tubes broke either in transit or during the unpacking at Solar Furnaces. This resulted in having two tubes, one 22-inches-long and the other 18-inches-long. Figure A-2 shows the tubes in the packing box after they have been removed from the shrink-wrap in which they were encased.



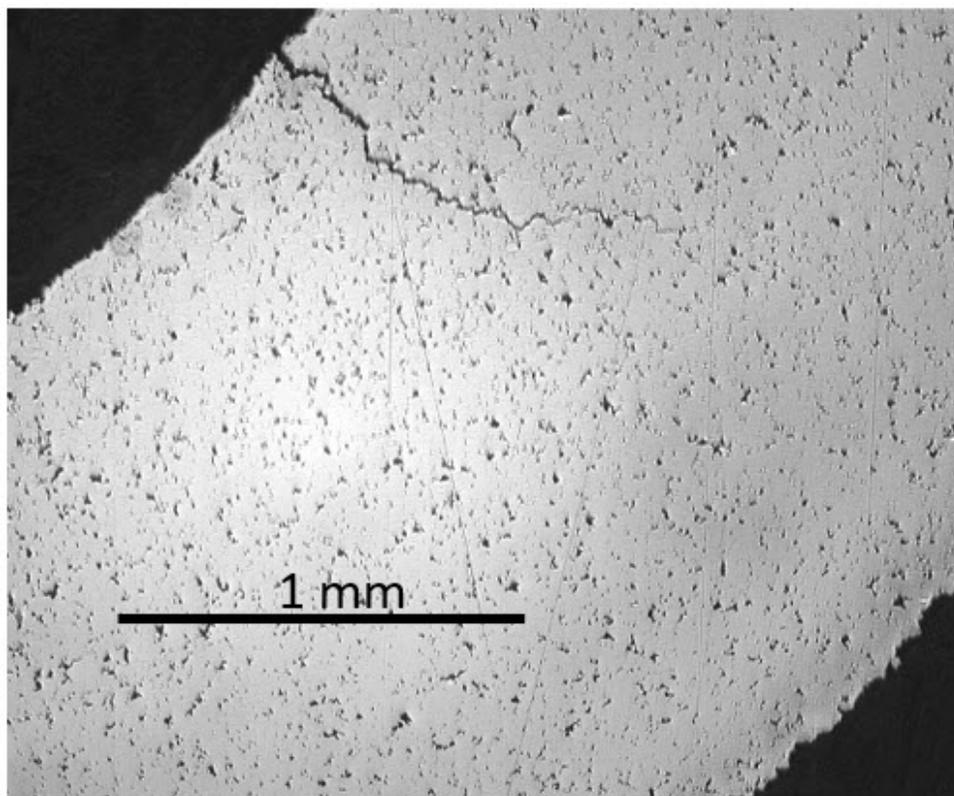
**Fig. A-2 Cold-sprayed Biodur tubes after unpacking at Solar Atmospheres. One of the tubes has been cracked, forming 2 pieces.**

Solar Furnaces heat-treated all of the parts, including a 4-inch piece of scrap, and returned them to ARL. The treatment called for a temperature rise up to 1875 °F under high vacuum, followed by a switch to a partial pressure of argon. The temperature was then raised to 2050 °F and held for 1 h. The parts were then quenched in argon.

The hardness values of the heat-treated and nonheat-treated tubes were measured with a Wilson Tukon Knoop/Vickers Hardness Tester with a 50-g load. These measurements are shown in Fig. A-3. The variation of hardness for the heat-treated tube is lower than that of the nonheat-treated tube, likely due to the better processing parameters of the former. A micrograph of a sectioned sample of a heat-treated tube is shown in Fig. A-4. Hardness measurements were made on the heat-treated tube before final machining. Consequently, the nonheat-treated tube wall thickness is thinner than that of the heat-treated tube.



**Fig. A-3 Comparison of hardness data from heat-treated and nonheat-treated Biodur tubes. The former has a thicker wall since the measurements were taken before machining.**



**Fig. A-4 Cross section of a Biodur heat-treated tube. It is unknown whether the observed crack in the tube occurred as a result of the heat-treating process or was there prior.**

A sample of the Biodur powder was sent to Luvak, Inc., Boylston, Massachusetts, for chemical analysis. In particular, the carbon content was requested. This was done to assure the carbon content met the specification on the purchase order to CarTech. Luvak reported that the carbon content was 0.012%, which was actually lower than what was requested.

A second attempt was made by the ARL machine shop to produce a Biodur tube with the correct dimensions. Upon putting the first tube in the lathe, the Biodur tube cracked in the chuck. The cracked portion was cut from the tube and another attempt was made to machine the tube. Even though the outer surface of the tube could be machined to the final dimension, the inner surface could not. The tube cracked at the end where the tool was inserted and no material could be removed from the inner surface.

This was the last attempt to machine a Biodur tube at ARL. The possibility of this material being machined through the water jet process is currently being pursued at Ormond, LLC in Auburn, Washington.

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## **Appendix B. Emplacement Parameters and Comments**

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**Table B-1 Processing parameters and comments**

Pass no.	Tube 1			Tube 2		
	PR (inches)	EL (inches)	Comment no.	PR (inches)	EL (inches)	Comment no.
1	22.5	1.35	...	22.5	1.29	...
2	21.0	2.50	...	21.5	2.50	...
3	19.0	5.06	...	20.5	3.44	...
4	17.5	6.81	...	19.0	5.04	...
5	16.0	8.69	...	17.5	7.48	...
6	15.0	9.81	...	16.0	9.39	...
7	13.0	10.0	...	15.0	10.0	...
8	11.5	13.6	...	13.0	11.99	...
9	9.0	16.38	...	11.5	3.85	...
10	7.0	18.63	1	9.0	16.50	...
11	16.0	8.69	...	7.0	18.88	2
12	17.5	6.94	...	15.0	9.88	3
13	19.0	5.19	...	15.5	8.25	...
14	20.5	3.50	...	16.5	7.38	...
15	21.5	2.63	...	19.0	4.50	...
16	22.5	1.35	4	20.5	3.00	5

Comments:

- 1) The barrel was flipped upside down for the next pass.
- 2) The bottom seal broke; it was replaced with a new seal. After restart, the push rod (PR) buckled at a load of approximately 11,000 lbs. The barrel was flipped upside down for the next pass.
- 3) The PR buckled at a load of approximately 14,000 lbs. The usual 10 min at load was not achieved.
- 4) A load of 14,000 was achieved and held for several minutes before the bottom seal broke. Processing was considered completed at this point.
- 5) The bottom seal broke at a load of approximately 9,000 lbs. Processing was considered complete at this point.

## List of Symbols, Abbreviations, and Acronyms

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ARL	US Army Research Laboratory
ARDEC	US Armament Research, Development and Engineering Center
CarTech	Carpenter Technology
CCM	Co, Cr, Mo
EL	elastomer
FPL	final plastic length
GLEEM	Gun Liner Emplacement with an Elastomeric Material
PR	push rod

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