CDR Engineering

Manufacturing Processes of a Built up Barrel

Reinforced, Lightweight Barrels for the Modern World

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Executive Summary

Our team will focus on the design of a built up barrel for the purpose of making a lighter/stronger barrel/pipe for use in defense applications. The requirements for the barrel are that the bore diameter be 130mm, the length be 51 calibers (6.63m), and to operate at a peak pressure of 600MPa. This means that a fairly heavy and long tube needs to be supported at the turret, meaning the lighter it can be, the better. The significant pressure of 600MPa is also another challenge to work with that directly ties in with the weight of the barrel. Autofrettaging and building up the barrel can induce residual stresses into the gun tube that reduces the peak stresses experienced by the barrel. This allows the barrel to be made lighter and have a longer life. Protective coatings on the interior and exterior surface will also increase the lifespan of the barrel. The barrels will be of exceptional quality to meet the demands of the military-industrial complex.

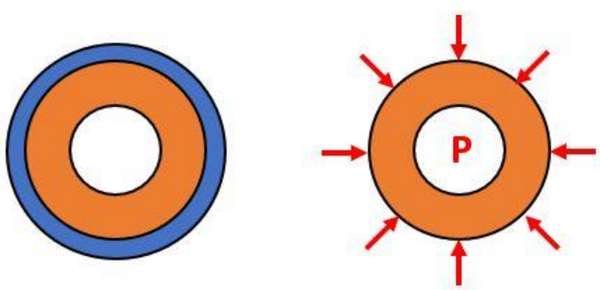

Figure 0. Built up barrel example.

Built up barrels operate on the principle that inducing a residual stress at the interface of two concentric tubes allows the inner tube to experience a greater pressure. By using thermal expansion of the tubes, one can be fit upon another creating a residual stress once shrunk. This residual stress helps counteract the high stresses within the gun tube allowing for higher maximal stresses. The barrel will also be smoothbore for the use of APFSDS rounds. Using the production methods outlined in this paper, estimates of the time and funding required to produce a capable barrel by these methods are 15.3 hours per piece and 5,143.23 dollars per piece respectively.

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INTRODUCTION

Explanation of Built Up Barrel

The method of barrel manufacture that was decided upon was a built up barrel. The other option was autofrettaging, but a built up barrel was found to be the simpler of the two methods to use and implement. To help explain, the figure below can be examined. It can be seen that the peak hoop stress due to gas pressure peaks at 360 MPa, though when combined with the hoop stress due to the shrink fit, its peak resultant hoop stress is 250MPa. This means that the barrel can be made lighter for the same pressure as the volume of material needed for the barrel is reduced.

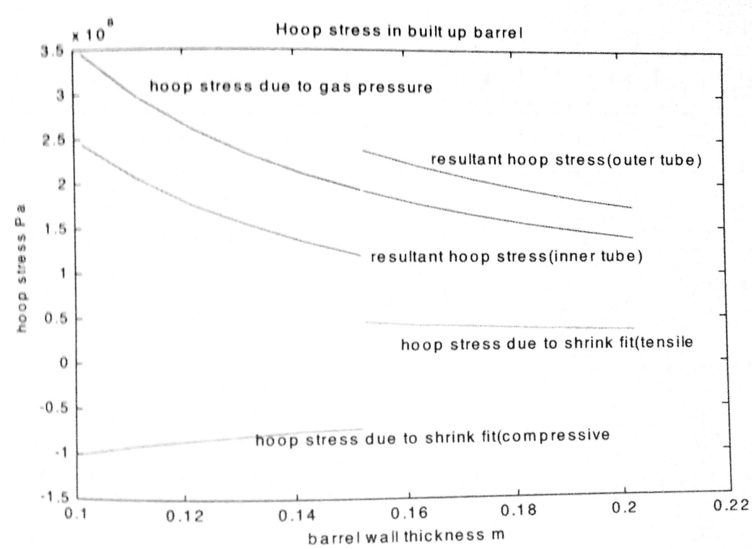

Figure 1. Example of stresses in a built up barrel.

In general, this method would be easier to manufacture than the autofrettage method, which will save costs in manufacturing. The method for a built up barrel is shrink fitting the outer sleeve, which can be done by heating the outer sleeve up and placing it over the inner sleeve, which is similar to how gears and bearing can be heat shrunk onto shafts.

Team Qualifications

Dylan Holtzhauer - Design Lead - Senior mechanical engineering student at Clemson University with an internship at a CNC mill and lathe manufacturer. Personal interest in researching gun tube design.

Colin McNeely - Materials Procurement - Junior mechanical engineering student at Clemson University with an interest in mathematics. Relevant coursework in SolidWorks, MATLAB, mechanics of materials, and thermodynamics.

Dillon Dubbs - Manufacturing Engineer - Senior mechanical engineering student at Clemson University. 2 Co-op rotations as manufacturing engineer with Bosch Anderson. Relevant coursework include Solidworks, MATLAB, mechanics of materials.

Riley McDowell - Project Manager - Junior mechanical engineering student at Clemson University. 2 Co-op rotations as a manufacturing engineer at Itron Inc. Relevant coursework in MATLAB, SolidWorks, machine design, manufacturing, and mechanics of materials.

Project Management Plan

A well-managed schedule was an essential part of the built-up barrel design process. In order to produce consistent, reliable progress the following schedule was produced which outlines the overall progress week by week over the last nine weeks. Week by week, these were the expectations decided upon to stay on schedule and produce the desirable results seen fit for this operation. Meetings were scheduled on an as needed basis with Zoom as the typical platform supplemented by an open communications line in Groupme. Highlighted cells specify which weeks a specific task was focused upon. In weeks prior to the creation of the schedule, a couple meetings were held to decide upon the task at hand and which procedures to implement in order to manage the project in an efficient manner. Note that some tasks took longer than others, but when put together, all tasks were completed and fit well into the schedule below.

Time Schedule	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9
	2/14 - 2/20	2/21 - 2/27	2/28 - 3/6	3/7 - 3/13	3/14 - 3/20	3/21 - 3/27	3/28 - 4/3	4/4 - 4/10	4/11 - 4/17
Identify Suppliers									
Analytical Calculations									
Built-up Barrel Design									
Heating Apparatus									
Outer Coating									
Inner Coating									
Solidworks Design									
Identify Other Tooling									
Production Design									
Validation Design									
Design Critique									
Present Results									

Table 1. Project management schedule.

Design Specifications

Cost of Initial Sleeves

It was found that the cost of the sleeves would be able to be quoted by weight, at a cost of $500 per metric ton for a metal with an appropriate yield strength. The combined weight of the two tubes is 4500kg, meaning the tubes cost $2250 to purchase. The initial sleeves will be shipped to the factory and be moved by forklifts.

Dimensions of the Sleeves

To make the barrel withstand the pressures of firing, the sleeve dimensions had to be chosen such that when the pressurized barrel works against the residual stresses from the built up barrel, it doesn't overcome the material properties of the barrel and fail. To determine this, a MATLAB file was created to determine the internal stresses in the barrel at peak pressure. The MATLAB code can be seen in Appendix A. It was determined for there to be 0.9mm interference at 210mm, with an outer diameter of 250mm. Therefore the dimensions of the sleeves would be 130mm ID with 210mm OD, and 209.1mm ID with 250mm OD, which results in a peak stress of 420MPa well below the yield strength of our selected steel. Below in Figure 2. is the relationship between the stress in the barrel from firing and the radius.

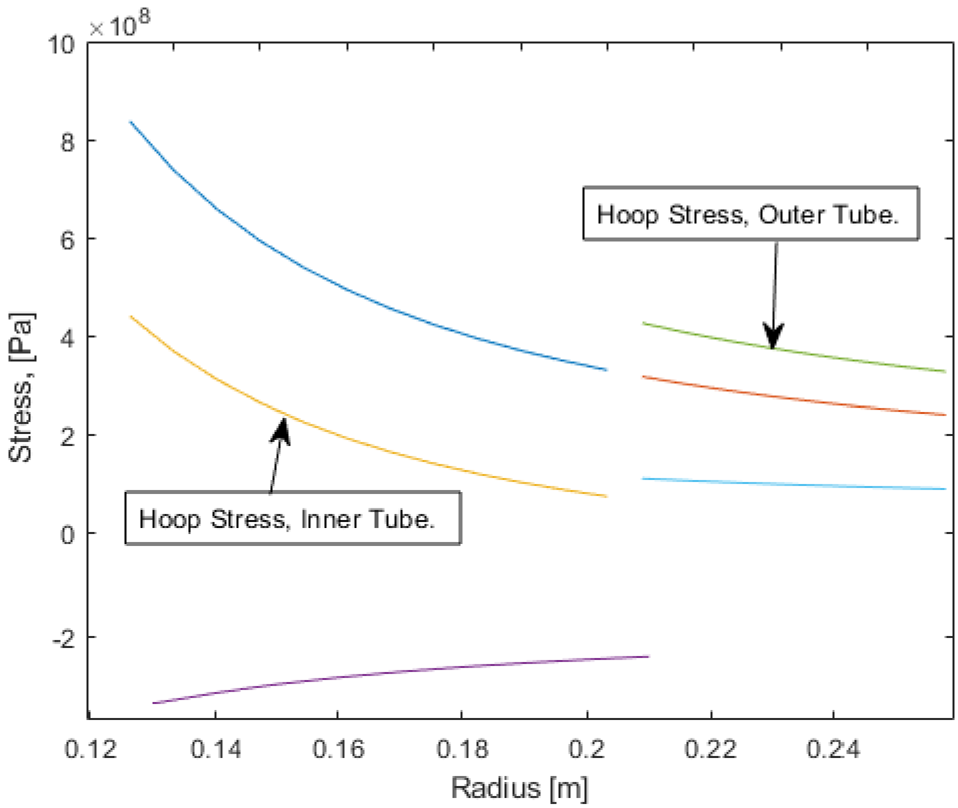

Figure 2. Barrel stress plot.

Manufacturing Process Design

For this facility, a process layout utilizing separate departments for each process will be used to best produce each barrel. Each process requires multiple workers and is a discrete process in and of itself. Keeping workers and production processes departmentalized will keep the facility organized and improve consistency. Due to the nature of the product, production will consist of low to medium-quantity production rates that are highly dependent on the product demands of the customer.

Unfinished barrels already cast to size will be shipped in from a separate wing of the company. This facility will only focus on strengthening and coating the barrels for shipment to the buyer. Doing so will lower the complexity of the facility, and prevent possible hazards related to pouring molten metal.

Fitting Sleeves

For the interference fit to take place, the outer tube needs to be heated to expand it. While the outer barrel is heated, the inner tube will be placed on a rod to hold it at the correct height and position. While the heated outer barrel is removed from the continuous mesh belt furnace, it will be slid onto the inner sleeve at the end of the furnace. For how hot the barrel needs to get, which is 386.3°C, it was calculated that with an 80% efficient 250kW furnace, the part would take an hour to heat. This leads to the speed of the conveyer being 1.83mm/s. Also, using the cost of electricity in South Carolina, it was determined that each barrel would cost $31.98 in electricity per barrel to run the furnace. A capable furnace was sourced from Vibrant Thermal Engineering for $375,000. Appendix B shows the calculations for all these values.

Figure 3. Continuous mesh belt furnace from Vibrant Thermal Engineering. [2]

Outside Coating

Before the internal coating is applied, the barrels need to be moved via forklift to the external coating machine. The operator assists the forklift driver in positioning the barrels to allow the machine to pick them up and transport them with ease. The machine then picks up a barrel and rotates it to allow for an even 0.5mm coating. This operation is performed under the watch of a single operator who will also be in charge of cycling the paint containers and changing out the tubes that apply the paint to the barrels. It is essential that these paint application tubes be exchanged and cleaned daily to resist potential clogging, this setup time was estimated to take 20 minutes. The power cost for this operation is $0.50 based on the 40 second cycle time. The cost of the paint can be almost entirely dependent on the volume needed for each barrel based on the collection area in the base, to recycle excess material. As a result the paint cost for each barrel is $61.74, but with our increasing business, we can afford to order in greater quantities reducing this cost even more. With the overall operation being very similar to the steel drum painting operation shown below, the machinery cost was estimated to be $500,000.

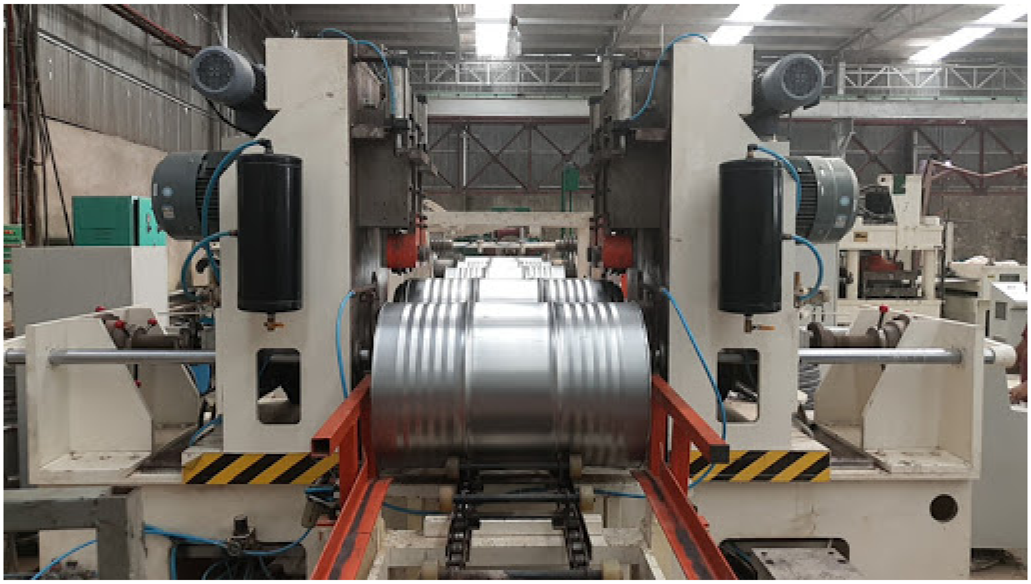

Figure 4. External Coating Machine [6]

Inside Coating

After the outside coating has set, the barrel will be moved by forklift to the next station within the facility. Two operators will assist the forklift driver in loading the barrel into a crane harness that doubles as an electrical cathode. The crane will move the barrel above a 7m by 1m by 1m pool intended for applying the trivalent chromium coating. The same two operators as before will assist with guiding the barrel into the pool and steadying the now submerged barrel. $0.05m^3$ of chromium chloride salts are then added to the vat by the workers. The barrel will only use $0.004015m^3$ of chromium to coat the barrel, but only about half of the salts by volume will coat the barrel, and the excess amount will aid in completely coating the inside of the barrel. Therefore, 22.96 kg of salt should be added to the vat to completely coat the barrels interior. The thickness of the chrome coating will ultimately be controlled by the amount of time that the barrel is submerged with the applied current. The coating should be approximately 0.0015m thick, which should take approximately 14 hours to complete at a rate of 0.10-0.125 µm/min.

The coating process is carried out by two electrical anodes that are lowered into the water. At this point, workers should be cleared from the area to avoid accidental electric shock. The anodes emit a current density range of approximately 8 amperes/square decimeter that completes the circuit through the crane cathode. This electrical current separates the chromium ions from the chloride ions in the salt. The chromium ions will then bind to the grounded inside diameter of the barrel. Workers can leave the workstation and simply monitor the barrels progress over the next 14 hours. After this time, the current should be switched off, a voltmeter should be used to test the water's charge for safety, and the barrel can be hoisted from the tank. One of the two operators at this station should clean the barrel by simply spraying it with a power washer. The barrel can now be loaded onto a forklift to be carried to the next station. The entire loading and unloading operation should be completed within 15 minutes. Tool handling time, including addings salts to the bath, should be completed within 5 minutes.

Chromium chloride was chosen as the primary salt for this process as it is more resistant to calcium chloride corrosion, which is a failure concern in harsh environments (Wardell). Trivalent chromium coating processes are also less toxic to workers and the environment. Most manufacturers that specialize in chrome coating currently use hexavalent coating processes, as it used to be the standard operation in the field. But, new environmental concerns will require these businesses to change their processes within the next 10 years. The EU has already requested that businesses switch to trivalent salts, and OSHA standards will soon require the same. By starting our manufacturing process with trivalent chromium coating in mind, we will save on conversion costs later. The cost of electricity should be less than $2.00 per barrel in the state of South Carolina at 12.56 cents per kW/h according to the SC Energy Office. Using prices from CarlRoth.com, the cost of chromium chloride per barrel will be equal to $2259.95, unless a deal can be reached between suppliers and the facility. The crane system will cost approximately $10,000 and the bath setup will also cost approximately $10,000. The final setup will be similar to, but larger than, the chrome plating bath shown below.

Figure 5. Chroming process. [4]

Manufacturing Validation Considerations

In order to properly present a finished product, some methods of testing must be implemented to make sure the final product is valid when subjected to real life forces. The primary physical property acclaimed by built up barrels is their exceptional pressure capacity. Thus the primary testing procedure will be to investigate the pressure capacities of the barrels. A common test used on most barrel designs is known as a proof test or a proof shot. A proof shot is a test wherein the barrel is exposed to pressures similar or higher than normal operating pressure simulating a round being fired. The chosen proof test was the standard modern C.I.P. proof test wherein two overloaded rounds producing 25% higher pressures than normal rounds are fired through the barrels to test their strength [7]. Numerous physical quantities will be measured including: chamber pressure, muzzle velocity, temperature change, and strain. The required instrumentation for measuring such quantities will be: a piezoelectric gauge for the chamber pressure, a doppler radar for the muzzle velocity measurement, multiple thermocouples for the inlet and outlet temperatures, strain gauge for the displacement measurements, and high speed photography.

Rendering of Barrel

3D renderings of the barrel are shown below in Figure 6 and Figure 7. Solidworks was used to create the following images.

Figure 6. Front rendering of the barrel.

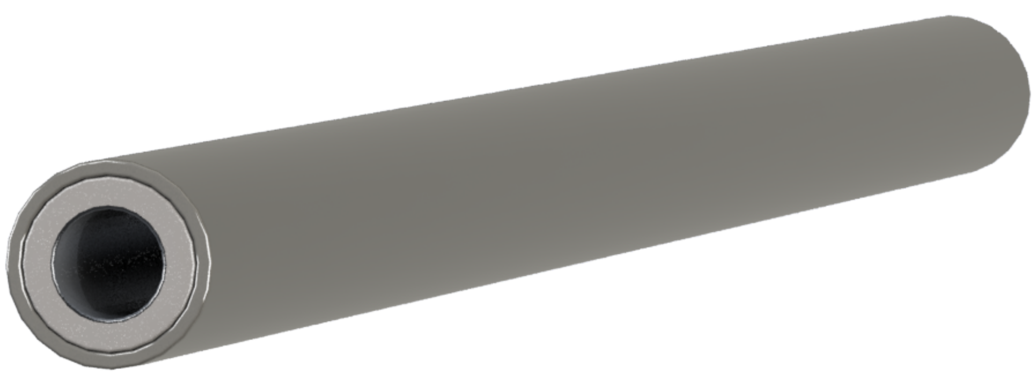

Figure 7. Side rendering of the barrel.

Conclusions

Operation	Total Time per piece[min/pc]	Total cost per piece [$/pc]
Production of barrel body	60.25	2330.18
Internal coating	860.05	2750
External coating	0.916	63.05
Total	921.216	5143.23

Table 2. Cycle Time and Part Cost

These prices include the cost of electricity and overhead with an operator pay of $25 an hour including overhead. This amount will be added on to the cost of shipping the barrels to and from the facility. Each barrel should sell to the buyer for approximately $9,000 after the markup.

CDR Engineering plans on selling the finished barrels to General Dynamics Land Systems in the United States. They are the leading manufacturer of armored vehicles in the United States, and our modern production facility will provide the product at a higher quality than our competitors, while meeting future OSHA standards.

Design Critique

It can be seen in Table 2 that the internal coating is the bottleneck in our production. With this knowledge CDR Engineering plans on purchasing more machinery for this operation, as orders become more frequent, in order to best correct this issue and greatly expand our production capacity at a limited cost.

Another method of improving the design of the barrel would be to autofrettage it, which induces stresses by plastically deforming the tube on the inside. It is a more efficient use of material than a build up barrel and would ultimately make the barrel lighter and use less material to produce. The heating section could also be omitted in place of pressurizing the tube.

Experts Credited

Use of Electroplated Chromium in Gun Barrels by Michael J. Audino and US Army RDECOM-ARDEC-Benet Laboratories is credited as the lead manufacturing expert for this report.

Large Caliber Gun Tube Materials Systems Design by J.S. Montgomery and R.L. Ellis is credited as another manufacturing expert for this report.

APPENDICES

APPENDIX A: MATLAB CALCULATION FILE

```
%Built Up Barrel
a=.13; %Inner Diameter
b=.21; %Interface Diameter
c=.25; %Outer Diameter

ar7=(a:.01:c);
r1=(a:.01:b);
r2=(b:.01:c);

p_i=600.*10.^6; %Gas Pressure
d=.9./1000; %Displacement
E=206.*10.^9; %Modulus of Elasticity

p=E.*d.*(c.^2.-b.^2).*(b.^2.-a.^2)./(b.*2.*b.^2.*(c.^2.-a.^2)); %Interface
Pressure

sigmaro=a.^2.*p./(b.^2.-a.^2).*(1-b.^2./r2.^2); %Radial Stress Outer
sigmato=a.^2.*p./(b.^2-a.^2).*(1+b.^2./r2.^2); %Hoop Stress Outer
sigamri=-p.*b.^2./(b.^2.-a.^2).*(1-a.^2./r1.^2); %Radial Stress Inner
sigmati=-p.*b.^2./(b.^2.-a.^2).*(1+a.^2./r1.^2); %Hoop Stress Inner
sigmarpi=a.^2.*p_i./(c.^2.-a.^2).*(1-c.^2./ar7.^2);
sigmatp_i1=a.^2.*p_i./(c.^2.-a.^2).*(1+c.^2./r1.^2);
sigmatp_i2=a.^2.*p_i./(c.^2.-a.^2).*(1+c.^2./r2.^2);
sigmat_res1=sigmatp_i1+sigmati;
sigmat_res2=sigmatp_i2+sigmato;
plot(r1,sigmatp_i1,r2,sigmatp_i2,r1,sigmat_res1,r1,sigmati,r2,sigmat_res2,r2
,sigmato)
```

Appendix B: Barrel Heating Calculations

$$d_1 = d_0\left(\delta T \cdot \alpha + 1\right)$$
$$210.9 = 210\left(\delta T \cdot 13 \cdot 10^{-6} + 1\right)$$
$$\rightarrow\ \delta T = 366.3^{\circ}C$$

Final Temperature= $366.3^{\circ}C + 20^{\circ}C = 386.3^{\circ}C$

Density of Steel= $8050\frac{\text{kg}}{m^3}$

Volume of Outer Sleeve= $\pi\left((.25m)^2 - (.21m)^2\right) \cdot 6.6m$

Volume of Outer Sleeve= $0.3815m^3$

Mass of Outer Sleeve= $0.3815m^3 \cdot 8050\frac{\text{kg}}{m^3} = 3071.2\ \text{kg}$

$$(10.1)\ U_{mp} = Cs\left(T_m - T_o\right) = 0.63 \cdot (366.3^{\circ}C)$$
$$U_{mp} = 230.769\ \frac{J}{g}$$
$$(10.2)\ \ H_{mp} = mU_{mp} = 3071.2\ kg \cdot 1000 \cdot 230.769\ \frac{J}{g}$$
$$H_{mp} = 708.738kJ$$

$$t = \frac{H_{mp}}{\mu \cdot P_{\text{furnace}}} = \frac{708.738kJ \cdot 1000}{0.8 \cdot P_{\text{furnace}}} = 3600s$$
$$\rightarrow P_{\text{furnace}} = 246kW$$

Speed of Conveyer= $\frac{6.6m \cdot 1000}{3600s} = 1.83\frac{\text{mm}}{s}$

Cost of Heating:

$$246kW \cdot \frac{1h}{\text{Barrel}} = \frac{246kw \cdot h}{\text{Barrel}}$$

$\frac{\$0.13}{kw \cdot h} \cdot 246\ \frac{kw \cdot h}{\text{Barrel}}$ =\$31.98 of electricity per barrel.

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