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CHARACTERIZATION OF BORE TEMPERATURES AND STRESSES IN SMALL CALIBER GUN BARRELS

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14. ABSTRACT

This project involves the instrumentation and testing of 7.62-mm machine gun barrels to characterize the temperature profile through the barrel wall and the strain experienced by the barrel during firing. The barrels are instrumented with commercial in-wall thermocouples and strain gages. The barrels will be fired at a variety of different schedules, and data will be measured and analyzed. The data from testing will be compared to analytical methods to assess barrel wall temperature profiles and barrel wall stress and strain. Results of the testing and the comparison to analytical methods will be used to further refine the methods used to analyze small caliber gun barrels.

15. SUBJECT TERMS

Barrel Gun barrel Small caliber Small arms Machine gun M240 Stress Strain Thermal Temperature Bore temperature In-wall thermocouple (IWTC) Strain gage

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INTRODUCTION

Currently in the small arms community, with the push for lighter, stronger barrels with improved life, a more complete understanding of the bore's thermal and structural behavior is required in order to not only improve future barrel design but to more thoroughly and accurately assess barrels in the current inventory. The environment within a small caliber gun barrel during a firing event is extreme. As a round is fired, hot, pressurized gases are produced, ranging in the thousands of degrees Fahrenheit (°F) and up to and beyond 62,500 lb per square inch [psi (ref. 1)] all within 1 ms. Moreover, in an automatic weapon such as a machine gun, the barrel's steady state temperature quickly increases as more rounds are fired in succession with the outer surface of machine gun barrels reaching higher than 1,000°F.

While the temperature at the barrel's outside wall can be easily measured in real time by a variety of means, the temperature at the bore or throughout the barrel's wall is much more difficult to characterize experimentally. Work done by Brosseau (ref. 2), and Foltz (ref. 3) have aimed to characterize the true temperature experienced by a 5.56-mm test barrel's bore and throughout the barrel's wall in real time. Work done by Drew et al. (refs. 4 and 5) has looked at measuring the temperature through a 5.56-mm M4 barrel's wall and correlating the data back to numerical computational fluid dynamics (CFD) modeling and simulation tools. Data from these studies has been correlated back to various modeling and simulation of the respective 5.56-mm barrels; however, there is no information available on 7.62-mm barrels, such as the M240L long barrel (fig. 1). Data and related modeling and simulation from a 7.62-mm barrel, when combined with the data and modeling and simulation from the 5.56-mm barrels, will help develop a better understanding of barrel heating in small caliber barrels and could help to increase the fidelity of the modeling and simulation tools used to predict barrel temperatures.

Figure 1
M240L long barrel

Stress analysis of small caliber barrels is currently done using calculations in the Army Materiel Command Pamphlet (AMCP), Engineering Design Handbook, Guns Series, Gun Tubes, AMCP 706-252 (ref. 6). There has been minimal work done to correlate test data back to the calculations outlined in AMCP 706-252 (ref. 6). While strain is easily measured, traditional strain gages are limited in their utility on a machine gun barrel due to the temperature that the outside of the barrel reaches during firing. Correlation of the strain measured in the hoop direction to the strain calculated using traditional methods from AMCP 706-252 (ref. 6) is critical to gaining a more thorough understanding of the barrel's structural behavior.

The purpose of the project is to characterize the temperature and stress in a 7.62-mm M240L long machine gun barrel (fig. 1) during a firing event using commercial sensors and data acquisition equipment. The data from testing is intended to be used to correlate and validate numerical CFD modeling and simulation to predict barrel temperature, much like that done by Drew et al. (refs. 4 and 5) as well as gun barrel stress analysis outlined in AMCP 706-252 (ref. 6). Temperature data will be measured with in-wall thermocouples (IWTC) from Veritay Technology, Inc., East Amherst, NY (ref. 7), and strain data will be measured with strain gages from Vishay Precision Group (VPG), Inc., Malvern, PA (ref. 8). The measurements will be taken in real time and at high sampling rates so that the true profile during the firing event can be observed.

BACKGROUND

5.56-mm Bore Temperature Assessment

An initial test was conducted with IWTCs on a 5.56-mm test barrel (ref. 3). For this effort, an electronic pressure, velocity, and action time (EPVAT) barrel, shown in figure 2 and originally developed for measuring down bore pressures (ref. 9), was modified to incorporate ITWCs at locations along the entire length of the barrel. Each gage was located along the grooves of the barrel's internal rifling, following the 1:7 twist rate. Similar to a standard EPVAT barrel, gage holes were located at the chamber and port. Additional gage locations were equally spaced 1 in. apart from the chamber down the length of the barrel in order to capture the change in bore temperature along the entire length of the barrel. In total, 13 holes were incorporated into the design of the barrel. Each hole location was drilled and tapped in accordance with figure 3. The IWTCs (fig. 4) require tip contact with the bottom of the instrumentation hole to make a junction. No reading can be obtained from these thermocouples unless they are properly installed in a specially machined instrumentation port. Holes were sealed with 10-32 stainless steel set screws when not instrumented. The thermocouples were threaded into full spring compression and then backed off 1/3 to 1/2 turn. Special attention was made to avoid spinning the thermocouples on their tips when installing and avoiding overtightening the thermocouples, which could damage the junction wires. A data acquisition rate of 10 Hz was used based on limitations of the setup.

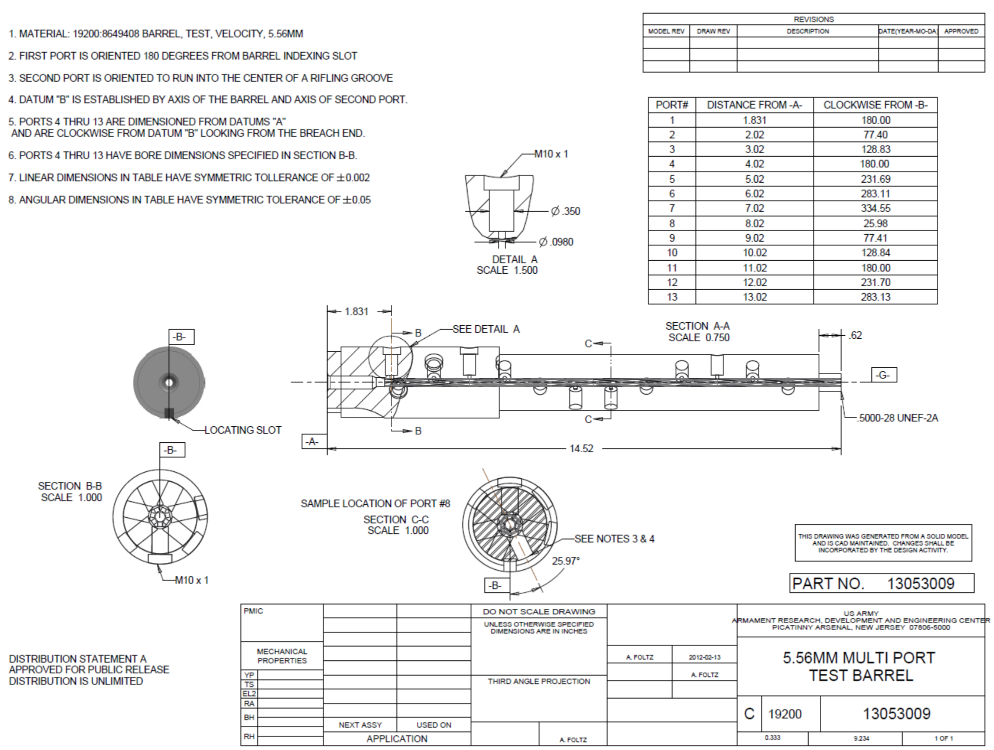


Figure 2
5.56-mm test barrel design

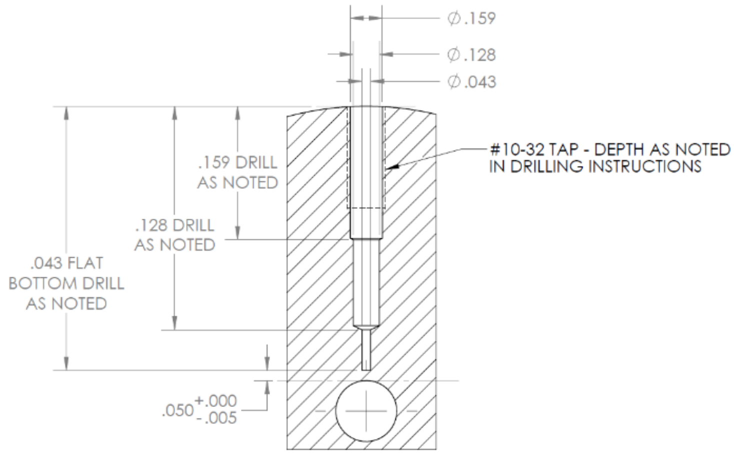


Figure 3
IWTC installation port

Figure 4
Veritay IWTC

Six different ammunition types were selected for the test in order to collect data along the entire range of possible pressure loads. For each ammunition type, projectile velocity, action time, and temperature along the length of the barrel was recorded using LabView software. Temperature data was collected from the time the primer was activated until the bore temperature was equal to ambient conditions. A series of 5 to 10 rounds were fired for each ammunition type in order to collect a range of temperature points across a single lot that could then be statistically evaluated for maximum temperature at each gage location.

Figure 5 shows a sample of the data collected for a single M855 shot in the 5.56-mm EPVAT barrel. Although the temperatures were measured at slightly different radial locations, the temperature data obtained in the test matched closely with the data obtained by Brosseau (ref. 2). The data at 1-in. axial increments all the way down the barrel added additional data to the Brosseau test, which measured at three different locations (ref. 2), and the Drew et al. tests, which measured at 10 different locations (refs. 4 and 5).

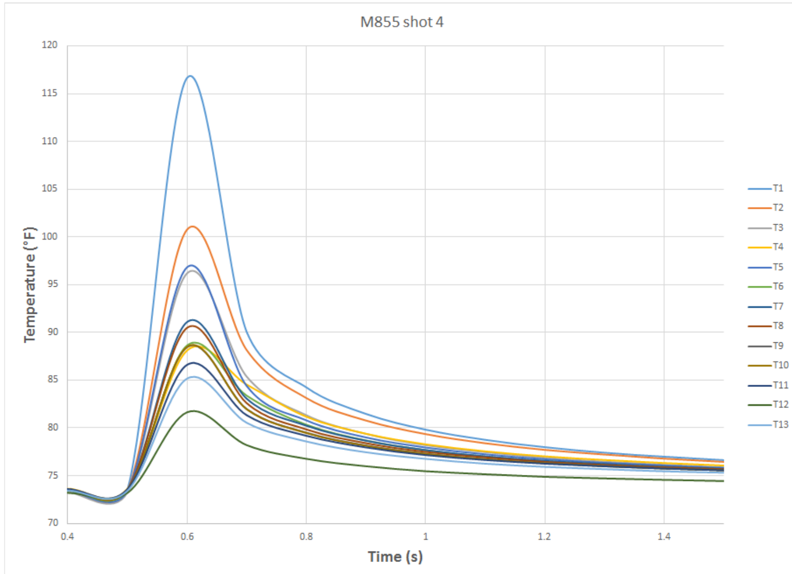


Figure 5
M855 sample temperature data

The results and lessons learned from the modified 5.56-mm EPVAT barrel test formed the basis of the current study. While the initial 5.56-mm EPVAT test as well as the work done by Brosseau (ref. 2) and Drew et al. (refs. 4 and 5) have provided a good understanding of the 5.56-mm barrel heating, data for the 7.62-mm caliber family of ammunition does not currently exist. Recommendations for future work included increasing the sampling rate to a minimum of 1 to 2 kHz (higher if possible), testing of different ammunition lots within the same ammunition type, and testing of different calibers. This additional data would help to develop a better understanding of all factors that affect barrel heating. Finally, rather than using a test barrel, an actual 7.62-mm machine gun barrel is desired so that temperature measurement could be made at firing schedules other than single shots.

STUDY METHODOLOGY

The 7.62-mm M240L long barrel was chosen because it was readily available for modification, it is capable of high rates of fire at elevated temperatures, and the long, untapered profile allows for ease of instrumentation along its length and ease of correlation to both hand calculations as well as CFD analysis. Internal barrel wall temperature and barrel strain will be measured at a variety of locations along the barrel. Strain will be measured exclusively on the outside of the barrel while temperature will be measured at various locations through the barrel's wall. Temperature testing will be performed at a variety of different firing schedules, resulting in a variety of different temperature profiles and heating rates, while strain testing will be performed primarily for single shots and short duration bursts. Data will then be correlated back to existing CFD modeling techniques (ref. 9) as well as barrel stress calculations outlined in AMCP 706-252 (ref. 6).

Test Barrel Design

Two different test barrels were designed and built to take the desired measurements of internal wall temperature and barrel strain since the strain gages would not be able to operate under the high temperatures that the temperature test barrel would see. The two barrels designed and tested under this effort were the temperature test barrel and the strain test barrel.

Temperature Measurement Barrel

While there are currently no empirical methods to measure the true temperature at the bore surface in real time and, therefore, to observe the instantaneous spikes that occur during the firing of the round, it is possible to measure the temperature as close as 0.050 in. from the bore surface using fast-acting IWTCs (ref. 7). In order to measure at these locations, the barrel must be modified to both mount the IWTCs as well as to permit the IWTCs to contact the barrel wall at the desired locations. The modifications made to the barrel are critical to the accuracy of the test and should be minimized since the intent of the test is to mimic an unmodified barrel.

The IWTCs require a minimum total mounting depth of approximately 0.6 in. to account for the features needed for mounting. Since it did not have the necessary wall thickness, the M240L long barrel was outfitted with mounting blocks to add the extra thickness needed. All mounting locations were aligned with a rifling groove in the barrel in order to permit accuracy and consistency from hole to hole. Each IWTC installation port was fabricated in accordance with figure 3 with the exception of the distance between the flat bottom of the hole and the bore surface called the measurement offset. In figure 2, the measurement offset is shown as 0.050 in. For the M240L barrel, the measurement offsets were 0.050 in., 0.150 in., and 0.250 in. in order to get a temperature profile through the barrel's wall at various locations. Figure 6 shows the modified M240L long barrel including the locations of the IWTC installation ports. The IWTCs were installed using the same method as the 5.56-mm IWTC installation.

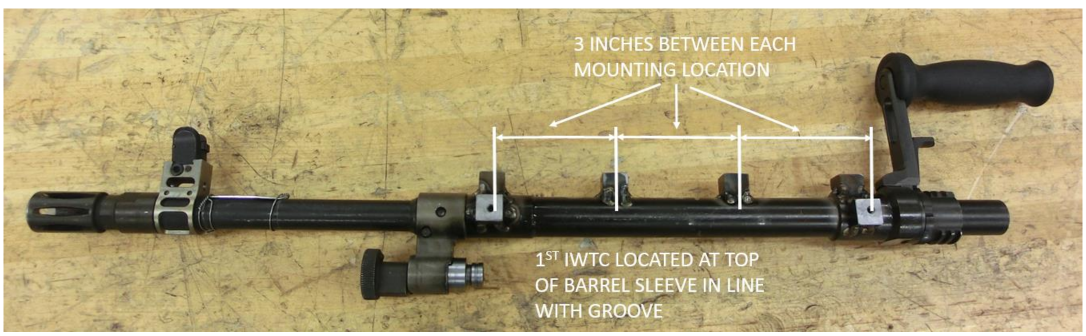


Figure 6
M240L long barrel with IWTC mounting modifications

A total of eight IWTCs were available for the test. The IWTCs were placed starting as close to the chamber as possible and then every 3 in. down the barrel up to the gas port. At each of these positions, the IWTCs were placed with a measurement offset of 0.050 in. In addition, at the positions closest to the chamber and closest to the gas port, IWTCs were also placed with measurement offsets of 0.150 and 0.250 in. in order to get a temperature profile through the barrel.

Strain Measurement Barrel

Stress and strain calculations for the gun barrel indicate that the stress and strain in the hoop direction are most prevalent (ref. 6). Thus, standard strain gages were selected to meet the criteria necessary to measure strain in the hoop direction of the M240L barrel. While there are high temperature strain gages available commercially, they require specialized skills to properly install and use and are typically used as a second or third order test rather than as a first attempt at measuring a phenomenon. Standard strain gages, while limited in temperature, require no special skills to install or use. The strain gage temperature limitations will be a primary driver for the firing schedules that can be tested since a machine gun barrel heats up rather quickly under even a moderately aggressive schedule.

Since the M240L barrel is a relatively small diameter cylinder, one must consider the diameter of the cylinder as compared to the gage length. Typically, a short gage length is desirable for installation on a cylindrical surface since the short gage length on a small diameter cylinder more closely approximates a flat installation. For this test, a 0.062-in. gage works nicely since it is large enough to easily install but is a small percentage of the barrel's radius, which closely approximates a flat installation.

The maximum estimated strain should be calculated using equation 1 (ref. 6) prior to gage selection in order to ensure that the gage limits are not exceeded.

$$\sigma_{hoop} = \frac{PD_i^2\left(D_o^2+D_o^2\right)}{D_i^2\left(D_o^2-D_i^2\right)} \tag{1}$$

Where:

P is the pressure,
D_i is the diameter at the bore, and
D_o is the diameter at the outside of the barrel.

Next, the equivalent strain on the outside of the barrel, or the hoop strain, can be calculated using equation 2.

$$\varepsilon_{hoop} = \frac{\sigma_{hoop}}{E} \tag{2}$$

Where:

ε_{hoop} is the hoop strain, and
E is the modulus of elasticity of the barrel material (28,000 ksi).

The estimated equivalent strain in the M240L barrel, using equation 2, is less than 500 microstrain. Using these parameters, the strain gage that was selected was C2A-06-062LW-350 from VPG (ref. 8). This gage has a gage length of 0.062 in., a strain limit of 30,000 microstrain, a temperature limitation of 180°F, and is prewired for ease of installation and compatibility with data acquisition and signal conditioning. This is a single direction strain gage, and, in accordance with the behavior of thick-walled pressurized cylinders, the gages were installed to measure strain in the hoop direction only. Figure 7 shows the C2A-06-062LW-350 strain gage installed on the M240L long barrel.

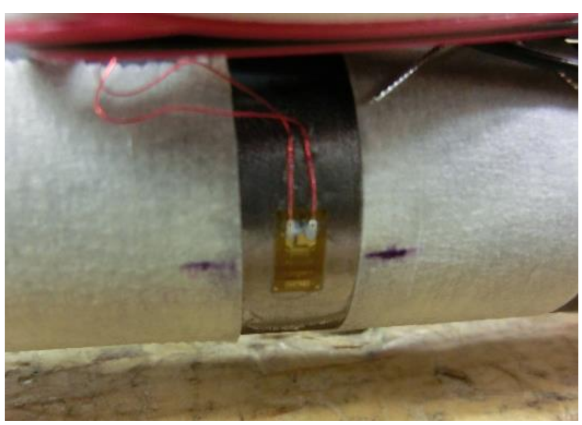


Figure 7
Strain gage mounted on M240L long barrel

It is important to instrument the barrel with strain gages in as many positions as possible in order to observe the strain at all barrel axial locations. As a starting point, strain gages were placed in axial locations corresponding to the IWTCs on the temperature barrel (fig. 6) so that data between tests could be correlated later if necessary. In addition, strain gages were placed at 1-in. increments between and beyond the corresponding IWTC locations down the full length of the barrel in order to maximize the strain data. Since the gas tube on the M240L is on the bottom of the barrel, all strain gages were installed at the top of the barrel with the heat shield removed. This allows the strain gages to be open to the surrounding air, minimizing any potential heat effects from firing.

Test and Analysis Procedures

At the time of press of this paper, the test has not yet been run. Test results are expected, however, for the International Symposium on Ballistics in September of 2017. The test will be run at the Armament Technology Facility, Picatinny Arsenal, NJ, on an indoor, climate controlled range. All firing will be conducted remotely with a mounted weapon system. Temperature and strain testing will be run separately. The M80 ball and M62 tracer ammunition from lot LC-07C603L664 will be used for the test. This is linked M80 ball (4 rounds) and M62 tracer (1 round) ammunition. Additional ammunition will be tested as available. Data acquisition will take place through the use of a DASH32 with a maximum sampling rate of 500 kHz.

Temperature Measurement Test

For the temperature measurement test, a variety of firing scenarios will be tested including single shots and various burst firing. Between each firing scenario, the test barrel will be allowed to naturally cool while data is being recorded. Data will be initially sampled at 2 kHz, as Veritay has indicated that this should be sufficient. The sampling rate will be increased if necessary. Beyond the data measured by the IWTCs, the temperature at the barrel's outer surface will also be monitored. The temperature data will be plotted versus time for each firing scenario and each measurement position. This data will then be compared to CFD results of the same firing scenarios. It is important to remember that the instrumented barrel and correlation to CFD will only be valid for the specific barrel and ammunition configuration being tested. Any changes to barrel material, barrel geometry, ammunition material, ammunition geometry, or propellant will likely result in the need to create new instrumented barrels and CFD models to predict the temperatures through the barrel's wall. At the locations where the measurement offsets of 0.050 in., 0.150 in., and 0.250 in. were all measured, a temperature profile curve through the wall will be generated, and the bore temperature can be extrapolated (ref. 2).

Strain Measurement Test

The main intent of the strain measurement test is to assess the stress level at the outside surface of the barrel during a firing event and then correlate the measured strain back to the calculated theoretical stress. Since the strain gages are only good up to 180°F (ref. 8), firing schedules will be selected in order to prevent the barrel from heating beyond the limits of the strain gage, starting with single shots. Barrel temperature will be monitored during the test to ensure that the strain gage temperatures stay below the limits. The stress imparted by the pressurized gas at each position down the barrel can be calculated theoretically by using documented pressure versus travel data (refs. 10 and 11) and equation 1 (ref. 6). The stress values calculated this way can then be compared to the measured strain/stress values from the test.

The sampling rate for strain measurement is an important consideration when considering the desire to measure the strain imparted by the engraving bullet, which is not accounted for in the pressure calculations. Since the projectile is traveling at a high rate of speed past each strain gage, it is important to carefully consider what the minimum sampling rate would need to be in order to obtain a relatively smooth strain curve for each gage. As a worst-case scenario, it can be assumed that the projectile is traveling at its muzzle velocity of around 2,750 ft/sec (ref. 1), and that the projectile's bearing length in the bore is roughly equivalent to the caliber, 0.300 in. If it is also assumed that the strain gage has a negligible width, the total time for the projectile to pass the strain gage is 0.0000089 sec. This means that with the maximum sampling rate of the DASH32 of 500 kHz, a bullet passing by a strain gage could result in as little as four data samples. Data will have to be assessed to determine if the sampling rate is fast enough to provide smooth curves and realistic peak values.

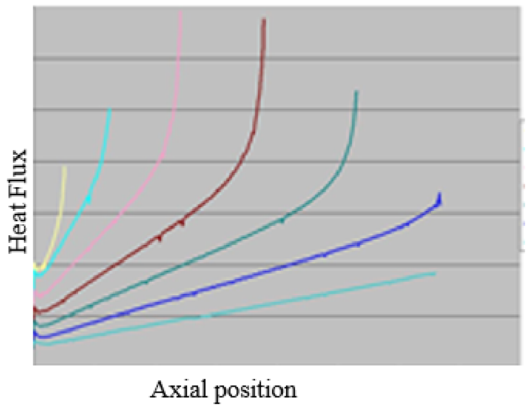
Correlation of Test Data to Numerical Solutions

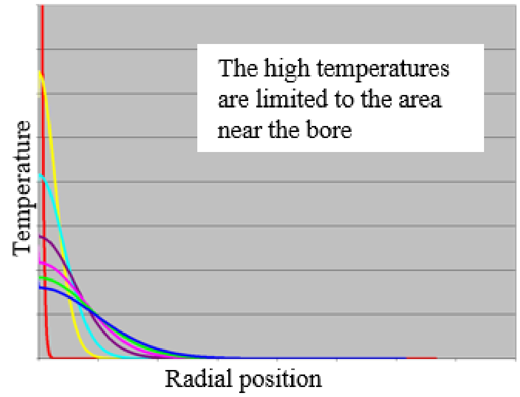
Temperature Measurement Correlation

Test data will be correlated to current state of the art computational physics based numerical simulations of the heating of the barrel. These simulations can provide detailed information on the radial and axial variations of the temperature and heat flux within the barrel including the variation from the bore to the outside surface. These numerical experiments are conducted in a controlled environment where measurements of the temperature can be made at any location from the bore to the outer surface and from the chamber to the muzzle at any time. Measurements are made without disturbing the heat flow in the barrel, and the values obtained are not limited by the test equipment. Because the barrel material properties and strength are temperature dependent, an understanding of the temperature distribution throughout the barrel, radially and axially, influences how barrel life and conditions can be improved.

A technique for numerically modeling the heating of a barrel resulting from the firing of successive rounds has been developed (ref. 9). The axial and temporal variation in the heat transfer coefficient and gas temperature from the chamber to the muzzle are determined from a conjugate heat transfer analysis. This data is applied as boundary conditions at the appropriate frequency in a model with the solid components only so that a given firing rate or firing schedule can be simulated.

The temperature and heat flow characteristics within the barrel can then be analyzed from the detailed information resulting from the simulations. With each round fired, energy moves into the barrel with the highest heat fluxes occurring as the hot, high velocity propellant gases pass over the bore and then diminish by several orders of magnitude (fig. 8a). As a single pulse of heat enters the barrel bore, the high temperature zone is restricted to a small radial distance from the bore surface. Though the heat flow (temperature rise) propagates radially, the affected area is less than half of the barrel thickness (fig. 8b). Thus, the outside surface of the barrel experiences a minimal response to the heat input by the single shot, which is something difficult to measure experimentally. As multiple shots are fired and heat is successively input into the barrel, each pulse causes the temperature of the barrel to rise, and the bulk temperature of the barrel material increases. The heat transfer and temperature rise eventually reach the outer surface of the barrel (fig. 9b). The distinct effect of the individual shots does not reach the outer surface. Even a few millimeters from the bore, the temperature levels and temperature gradients are significantly reduced (fig. 9a). The individual shot and radial gradient information cannot be obtained from the outer surface data (fig. 9a)

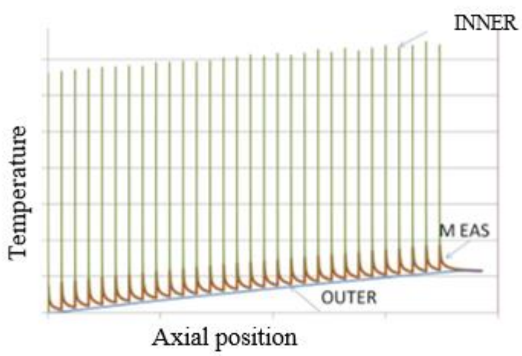


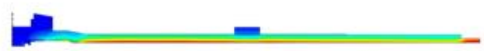


(a)
Single shot axial distribution of heat flux

(b)
Single shot radial distribution of temperature

Figure 8
Temperature and heat flow characteristics within the barrel



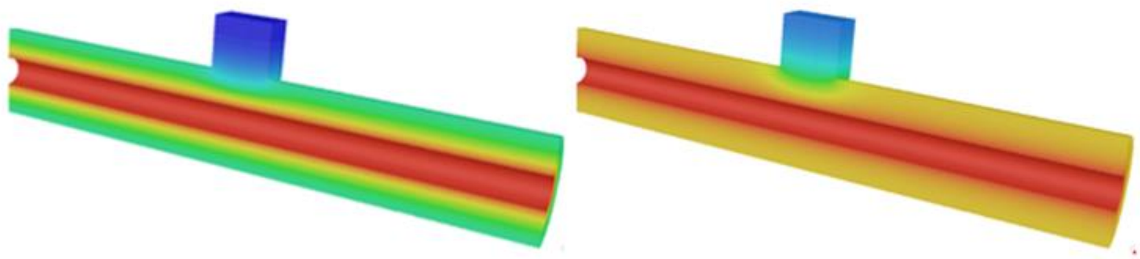


(a)
Multi-shot transient temperature

(b)
Temperature contours

Figure 9
Heat transfer and temperature rise outer surface of the barrel

In order to obtain more information about the radial distribution of the heat transfer through the barrel, experimental and numerical investigations are being conducted. Recall that in order to insert IWTCs through the barrel wall, the test configuration requires significant additional material attached to the outer surface of the barrel along with drilling of the hole in the barrel to allow for the IWTC placement (fig. 3). Numerical simulations were conducted for a system with a straight standard barrel section as well as a barrel section modified for the installation of the IWTCs. The results of the simulations clearly show that as firing continues and radial temperature gradients persist, the additional material from the instrumented barrel test configuration affects the local temperature distributions with the differences increasing with closer positioning to the additional material axially and radially (figs. 10 and 11). Figure 11 shows the radial temperature distributions for the standard barrel at the thermocouple axial location and 10-mm downstream (standard/thermocouple, standard/ thermocouple +10 mm) and the modified barrel (test/ thermocouple, test/ thermocouple +10 mm) at the same axial positions and at the same time. Clearly with the standard barrel, the radial temperature distribution does not vary with axial position. The lower temperatures with the test fixture and the axial variation indicate the influence of the additional material. The results demonstrate the potential alteration in the temperatures caused by the test configuration. As the temperature gradients diminish after firing, the additional material does not significantly alter the temperature distribution for the conditions studied.



(a)
Immediately after firing

(b)
After 10 sec

Figure 10
Temperature contours of modified barrel

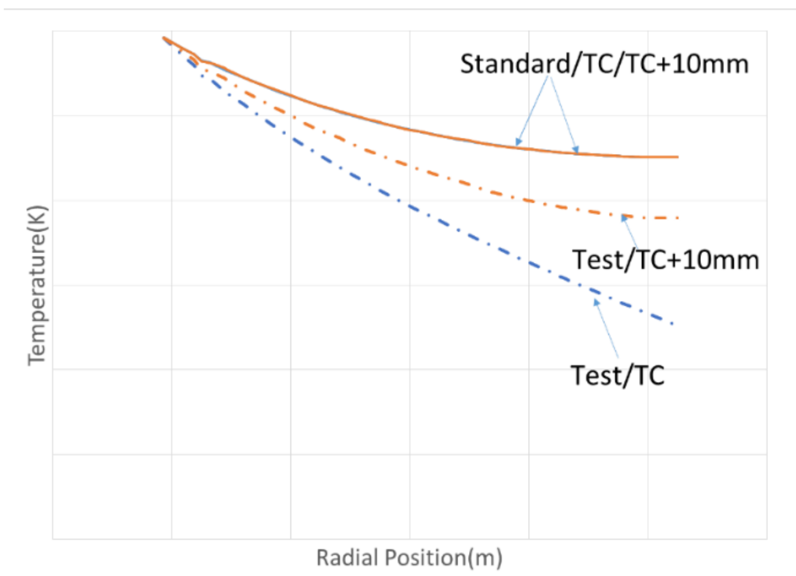


Figure 11
Radial temperature distribution comparisons

Strain Measurement Correlation

Strain measurements will be converted to stresses using equation 2 in order to assess the stress level at the outside of the barrel. The stress levels will then be compared to the stress calculated using equation 1 (ref. 6). Any differences in calculated versus measured stress will be assessed and discrepancies will be investigated to include potential error caused by the dynamic effect of pressurization, assessment of bullet resistance stresses, and other potential sources of error. Depending on the correlation of measured versus calculated stress, the stress at the bore will be estimated. Calculations in AMCP 706-252 will be assessed, and changes will be recommended if necessary.

CONCLUSIONS

The temperature and strain testing and data correlation being conducted represents a major increase in the knowledge and understanding of the behavior of the gun barrel during various firing events. In addition, the correlation of the data to numerical assessment methods will further refine the tools used to assess barrels and new barrel designs.

The results of the modeling and simulation of the temperature test barrel indicate that the in-wall thermocouple mounting modifications result in localized differences in thermal response as compared to an unmodified barrel. The takeaway is that the temperatures measured through the barrel wall will not accurately represent the temperatures that the actual M240L long barrel would experience in these locations due to those modifications necessary to install the thermocouples. However, the model of the modified barrel and the corresponding test data can be compared. Modification to the model can be made to improve correlation to the temperatures in the same system including the effects of contact resistance. The models can then be used to estimate the radial temperature gradient for a better understanding of the temperature distribution in the barrel. The numerical and experimental data will provide additional insight into the radial variation in temperature in a heated barrel.

The results of the strain testing will provide important insight into the strain behavior of the barrel during the firing event. Particularly, the test data can be compared to stress calculations in AMCP 706-252 (ref. 6) to assess whether the high dynamic characteristics of the event have any impact on the strain that is actually experienced by the barrel versus the strain that is calculated using theoretical means. Additionally, the strain data can be used to attempt to look at the strain imparted on the barrel due to the resistance of the bullet itself as it moves down the barrel.

RECOMMENDATIONS

While this effort will provide a significant increase in the understanding of the machine gun barrel’s behavior, further testing and additional excursions are likely to be required. Further testing is recommended. Primarily, strain data with high temperature strain gages will provide insight into the behavior of the barrel as it heats up since the temperature profile through the barrel creates a complex thermal strain gradient in addition to an already complex response to temperature dependent material properties. In addition, further testing should include different ammunition types and different lots of ammunition to look at ammunition dependent variation. It is also recommended that a bullet pull test be performed with carious ammunition to look at the strain resultant of only the bullet moving down the barrel.

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