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BARREL WEIGHT REDUCTION

Greg Livermore
FN Manufacturing, Inc.
797 Old Clemson Road
Columbia, SC 29229

Lucian Sadowski
Project Engineer
ARDEC

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ARMAMENT RESEARCH, DEVELOPMENT AND
ENGINEERING CENTER

Armaments Engineering & Technology Center (Benet)

Picatinny, New Jersey

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SUMMARY

This report describes the program funded under contract DAE30-03-C-1129 to reduce the weight of the 5.56-mm M249 barrel. Using the MK46 barrel as a baseline and implementing the use of a full Stellite liner with state-of-the-art UltraCem nickel-boride coating, the weight reduction was attained. Optimization of the barrel contour was completed using a variety of analytical methods prior to fabricating prototype barrels for testing.

This effort focused in large part on the theoretical and experimental analysis of the barrel. A modified MK46 barrel lined with Stellite 21 was optimized to take advantage of the fact that Stellite can retain its mechanical properties at much higher temperatures than those of the standard M249 barrel steel. The optimization analysis compared the new design to that of the standard MK46 barrel, which was used as the baseline. Finite element analysis (FEA) modal, static, dynamic, and transient thermal analyses provide the required metrics for the comparison. These metrics include dynamic response characteristics, deflection under dynamic loading, static stress, and temperature behavior under thermal loading. The FEA modeling was validated and adjusted using experimental results from the existing standard MK46 model.

In an effort to mitigate the abrasive wear on the Stellite liner, the surface characteristics of the Stellite liner were modified by applying UltraCem nickel-boride coating. The UltraCem coating was also expected to form a fine insulating layer that may impede heat transfer into the barrel interior. Less heat transferring into the barrel interior allows additional mass removal, since the mass was no longer needed as a heat sink. Due to the nodular nature of the Ultra Cem, this layer was very ductile, which makes it ideal for the cyclic type loading encountered inside the barrel.

An optimized barrel design was selected that reduced the MK46 barrel weight by approximately 0.25 lbs or 11%. Relative to the standard M249 barrel, the weight was reduced a total of about 1.95 lbs or 48%. Prototype barrels of this configuration were fabricated using an Fabrique Nationale Manufacturing, Inc. (FNMI) patented process, which was further refined during this program. Because of the unique nature of the Stellite-lined barrel design, considerable development of the UltraCem coating was necessary. Ten barrels were coated with UltraCem on both the Stellite lining and the steel barrel. Measurements indicated that further coating process development was necessary in order to achieve standard barrel dimensions. Seven of the 10 barrels were found to be acceptable for testing purposes, but the coating thickness and resulting barrel dimensions are not to specification.

Testing of five of the 10 barrels was conducted, including functional tests, dynamic motion measurements, and thermal evaluations. The results support the analytical results obtained during the barrel optimization and analysis efforts. Recommendations for further actions are provided.

INTRODUCTION

One primary focus of the Lightweight Family of Weapons and Ammunition (LFWA), a Joint Service Small Arms Program (JSSAP) effort, is on developing lightweight machine guns weighing 30 to 35% less than current systems. This reduction may result from the evolution of technologies developed for other weapon systems or the application of old ideas, which technological barriers heretofore prevented.

The M249 barrel weighs 4.05 lbs or approximately 23% of the total weapon weight. Including the spare barrel, any reduction of the barrel weight was effectively doubled. The standard MK46 5.56-mm machine gun barrel assembly weighs approximately 2.35 lbs, 43% less than the standard M249 barrel. This program was an attempt to further reduce that weight through the conception, design, fabrication, and testing of a full-length Stellite-lined barrel for the MK46 machine gun.

A standard 5.56-mm barrel contains a great deal of extra mass to act as a heat sink, which retards the rise of temperature in the bore. The mechanical properties of the standard M249/MK46 barrel steel rapidly deteriorate at higher temperatures, thus the need for the extra mass. However, if the bore material's mechanical properties do not deteriorate at higher temperatures, as was the case with Stellite, the extra heat sink mass can be removed. This task has assessed the amount of mass that can be removed without compromising the overall barrel performance.

The concept of a short Stellite liner was proven in battle-tested designs. Instances of this approach are evident in the M60E3, formerly produced by Saco Defense Corp., and the M3 .50 caliber family, currently produced by FN Herstal in Belgium.

A previous FNMI project developed a methodology to fabricate M249 barrels, fully lined with Stellite to satisfy the requirements of a task order under the M249 Systems Technical Support. The bulk of the effort focused on developing a fabrication process. This enabled FNMI to take advantage of its core competence in rotary forging and incorporate a steel over-wrap on a Stellite rod. The electrical discharge machining (EDM) methodology was used for deep-hole drilling and electro-chemical (ECM) was used for the rifling. While these are not typical production processes for these operations, the end product was a full-length liner that had never before been achieved. From there on, the resulting steel-Stellite rifled blank was processed as a normal M249 barrel. Several prototype barrels were fabricated, but they were not successful in extending barrel life when subjected to the United States Government (USG) live fire endurance tests.

Unlike the previously referenced efforts, this program focused on the analytical effort to develop and optimize a full-length Stellite lined barrel. This research area explored a weight reduction of the 5.56-mm barrel using the MK46 barrel as a baseline.

DESIGN

The new design encompasses the experience gained during the design of a M249 Stellite lined barrel, which is described in reference 1. It includes a Stellite 21 liner that extends the entire length of the barrel. The design was modeled in Pro/Engineer (ProE) and mechanical drawings were created for fabrication prototype parts. The rudiments of this design are shown in the barrel section in figure 1.

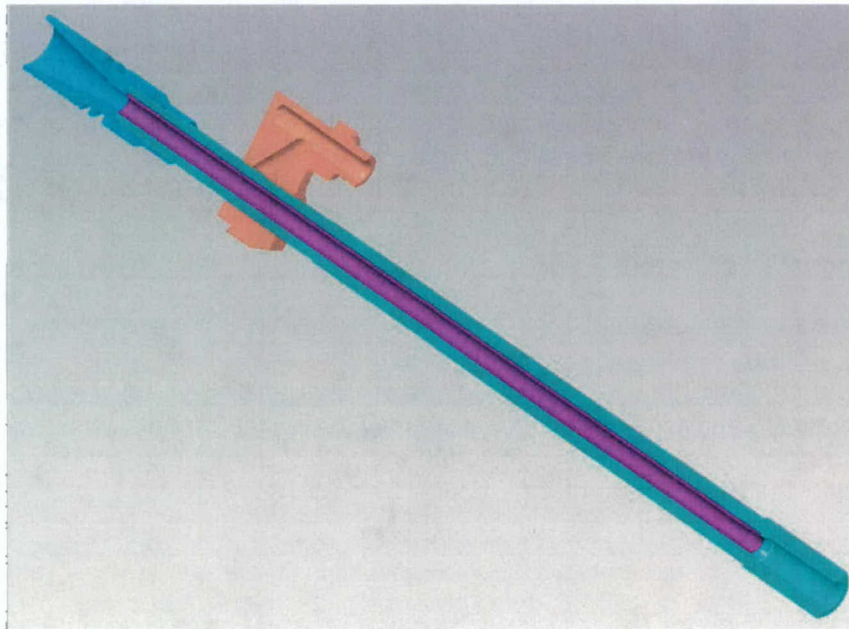


Figure 1
Stellite liner cross-section

OPTIMIZATION DESIGN CRITERIA

The barrel design has undergone an iterative development based on FEA results using the computer codes Pro/MECHANICA and ANSYS. The following design and optimization criteria were intended to provide a means to compare the planned design to that of the baseline standard MK46 barrel. For this purpose, the new barrel design was evaluated on the basis of the following attributes.

Structural Integrity

It was imperative to assess the effect of the design change on the structural integrity of the barrel. Weakening the barrel to reduce mass can decrease both the strength of the barrel and the overall accuracy of the weapon. The structural integrity of the new design was assessed by comparing it to the baseline design. The following characteristics of structural integrity were used for this comparison.

Modal Analysis

This FEA provided the natural frequencies of the barrel along with its modes of vibration. It was considered a good means to compare structural integrity, since it varies with changes in the mass and stiffness of the barrel. Since the barrel is a periodically forced system, its natural frequencies must be far away from the period of the forcing function; in this case the rate of fire.

Stress Analysis

The design change must not weaken the barrel to the extent that the stress resulting from the gas pressure will cause the barrel to either explode or fatigue due to the cyclic load. This new design stress must be kept in mind relative to the strength of the new material when subjected to the high temperatures encountered during operation. This design characteristic was assessed using FEA.

Dynamic Barrel Response

This design characteristic can be assessed by modal analysis alone, since the loading function and the constraints of the new design are not any different from those of the baseline design. In other words, the interfaces of the new barrel with the weapon do not change. Also, the loading due to firing is identical. However, FEA can yield additional information, to include the deflection and its rate of movement at the muzzle. These quantities were used to assess the effect of the design change on accuracy and dispersion.

Thermal Integrity

Barrel mass removal will typically have an adverse effect on thermal integrity. It is known that the heat supply into the barrel from the hot gas far exceeds the heat dissipated through convection and radiation at the barrel surface. For this reason, the heat accumulates in the barrel mass, and the greater the mass the longer it takes for the temperature to reach critical levels. Since the new design is intended to reduce mass, a new means must be devised to counteract this drawback. This design characteristic can be assessed using transient heat transfer analysis. This analysis should incorporate time dependent convection and radiation expressions in order to adequately define temperature and heat transfer coefficients. This variable dependency is characteristic of a firing cycle and adds an order of complexity to the model, which takes significant effort to define.

ANALYSIS

The barrel structural and thermal integrities were assessed by using FEA methodology.

Modal Analysis

Modal analysis examines the natural frequencies and modes of vibration for a given structure. In the case of a structure subjected to a periodic excitation, it is imperative that all of its natural frequencies are far away from the excitation frequency. In the case of the MK46 machine gun, the excitation frequency was that of the rate of fire, which was approximately 11.5 Hz. In this analysis, the natural frequencies of the standard MK46 barrel are used as a baseline. The natural frequencies of a MK46 with Stellite and those of a MK46 with Stellite as modified to reduce mass are compared to this baseline. The following modal analysis shows clearly that the three barrel designs differ very little with respect to natural frequencies and modes of vibration. This means that the structural response to the same mechanical excitation, such as firing a round, will be very similar.

Standard MK46 Design

The baseline design MECHANICA FEA model uses the ProE barrel model almost intact with minor de-featuring (removal of minor geometric characteristics) to facilitate the FEA process. The barrel was rigidly attached to the receiver. The gas cylinder was simulated as a simple beam rigidly attached to the receiver. Its interface with the barrel was allowed to rotate and translate about the gas cylinder axis; however, it was fully constrained in the remaining four degrees of freedom.

The first three harmonics of this design are shown in table 1 as 112.60 Hz, 184.57 Hz, and 586.55 Hz. The 112.6 HZ frequency represents a mode whereby the barrel oscillates horizontally (fig. 2). The 184.57 Hz frequency represents a mode whereby the barrel oscillates vertically (fig. 3). The 586.55 Hz was an S-shaped mode, whereby the barrel oscillates horizontally, but it has no design significance since it is too far away from the excitation frequency of firing.

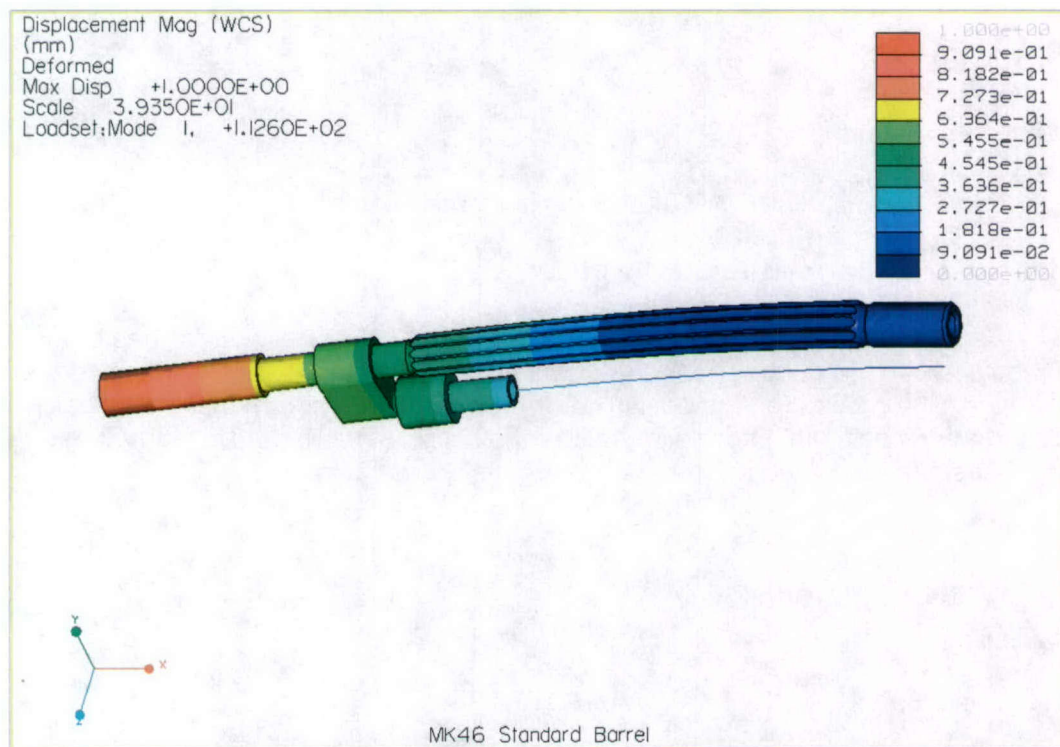


Figure 2
MK46 standard barrel

MK46 Barrel with Stellite Liner

Figure 3 shows the FEA model for MK46 barrel with a Stellite liner. The external configuration and its interfaces with the receiver and the gas cylinder are identical to that of the standard, baseline design. The calculated modes are almost identical to those of the baseline barrel (fig. 2). This is unremarkable since the elastic properties of Stellite 21 are very close to those of steel. Table 1 shows a detail mode comparison of the two Stellite lined barrels to those of the baseline.

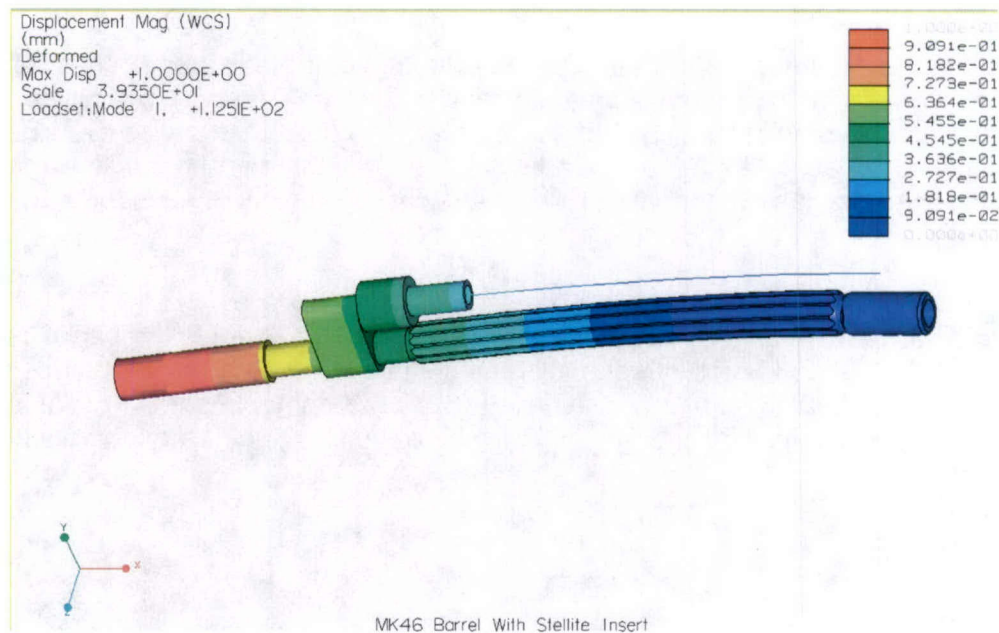


Figure 3
MK46 barrel with Stellite insert

Modified MK46 Barrel with Stellite Insert

Figure 4 shows the final design. It is noted that the barrel exterior has been modified; however, its interface with the receiver and the gas cylinder are identical to that of the baseline design. The modes for this design differ only very slightly from that of the baseline design, despite the significant change in the barrel exterior. A more detailed comparison of the two different designs relative to the baseline design is shown in table 1.

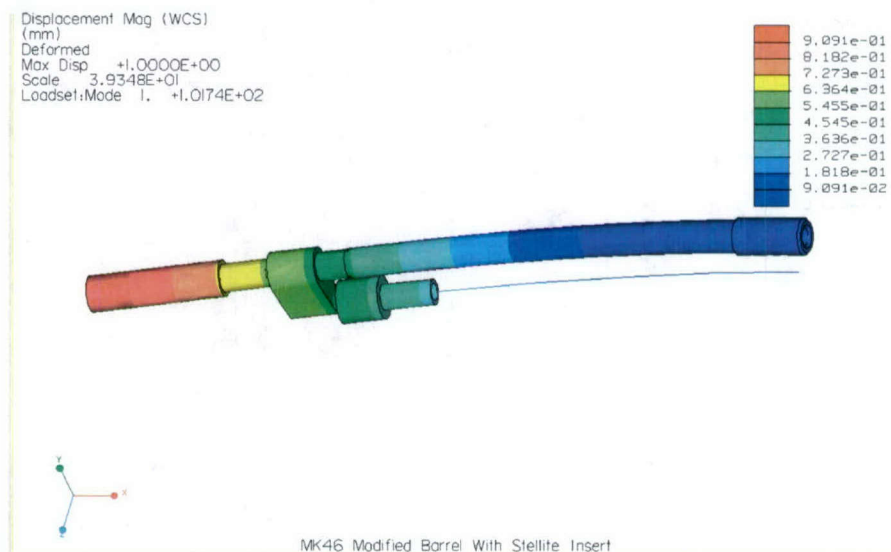


Figure 4
MK46 modified barrel with Stellite insert

Conclusions

Table 1 shows that removing mass from the baseline barrel design has an insignificant effect on the modal characteristics. The difference between the Stellite lined MK46 barrel and the baseline design was negligible. The change of the planned design first harmonic from 112.51 Hz to 101.74 Hz was insignificant with respect to proximity to the excitation frequency of 11.5 Hz. However, its effect on transient response is not known, and it will be investigated in the Structural Transient FEA.

Table 1
Mode comparison

Barrel designs	Mode1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)
Baseline	112.60	184.57	586.55
MK46 with Stellite	112.51	184.42	587.83
MK46 modified with Stellite	101.74	174.19	563.90

Model Validation

A standard MK46 barrel was instrumented with accelerometers and response of the barrel was recorded. A fast Fourier transform (FFT) was performed on the collected data. The results strongly suggest that the FEA predicted the correct natural frequencies. Therefore, it is reasonable to conclude that the model constraint conditions for the given geometry are representative of actual values. This means that the resulting analytical output for any subsequent design carries a high confidence factor for the geometry being analyzed.

Structural Dynamic Response

Loads

The FEA models developed for the modal analysis are fitted with the appropriate loading to obtain the barrel's structural transient response. These loads include the pressure in the barrel interior and the pressure at the gas block. The latter of these provides a forcing function that deflects the barrel vertically during firing. These pressures are measured experimentally by placing pressure sensors that communicate with the bore near the chamber and the gas block interior. The data are collected by means of an automated data collection system, and they include tables of pressures as a function of time for a single round.

Barrel Internal Ballistics

The experimental pressure tables that are functions of time, $P(t)$, must be converted into pressures as functions of location on the axis of the barrel, $P(z)$. This conversion allows the application of the appropriate pressure at each barrel location to correspond to the presence of the round at that point. This pressure conversion can be obtained by using internal ballistics as follow. From the momentum conservation law

$$\int_0^t P_s A dt - F \int_0^t dt = mV(t) \quad (1)$$

$$F = \frac{1}{t_m} \left[\int_0^{t_m} P_s A dt - m V_m \right] \quad (2)$$

where

P_s = Base pressure on the projectile

A = Base area of the projectile

M = Mass of the projectile

F = Frictional restraining force

t = Time after pressure increase

V = Projectile velocity

V_m = Muzzle velocity

t_m = Muzzle time

The value of t_m is estimated by setting it equal to $2x(\text{barrel length})/V_m$. This value is substituted in equation 2 to find F , which in turn is substituted in equation 1 to find $V(t)$. This provides a better estimate of t_m , which in turn provides a better estimate of F . This process continues iteratively until the value of t_m converges. The integration is performed numerically.

FEA Transient Analysis Model

The information derived from the internal ballistics calculations was used to determine the appropriate loading on the bore surfaces. This analysis scheme was repeated three times at a periodic rate, which equates to a firing schedule of 700 rounds per minute. This is representative of a three-round burst of fully automatic fire.

Muzzle Displacement and Velocity Model

The MECHANICA FEA model can be used for both dynamic time and static structural Analyses. The FEA model consists of the main barrel, which was fully divided into finite elements and the gas cylinder, which was simulated as a simple beam. The model includes geometry, constraint conditions, simulations, and pressure loading at the appropriate bore sections.

Geometry. The external geometry was almost intact with minor de-featuring to facilitate the FEA. Complicated geometry features that do not contribute structurally to the FEA model were geometrically simplified, while retaining their equivalent masses to provide better representation of the dynamic behavior. Examples of such features are the gas block, front

sight, and the flash suppressor. The barrel extension was not included in this model, and it was considered a part of the receiver interface. Moreover, the rifling features were suppressed, since the bullet-bore interaction was not considered in this analysis.

Constraints. The chamber exterior surface and the interface of the gas cylinder are fully constrained. The interface between the gas cylinder and the gas block allows a relative motion between connecting parts, which includes rotation about and translation along the gas cylinder axis only. This interface does not allow translation or rotation about the two axes normal to the gas cylinder axis.

Simulations. The gas cylinder was simulated by a constant equivalent cross-section beam, which retains the original cross-section area moment.

Materials. The material properties for this model are shown in table 2.

Table 2
Structural material properties

Material	Density (kg/m ³)	Poisson's ratio	Elastic modulus (GPa)
Steel	7827.80	0.27	199.95
Satellite	8387.04	0.30	209.60

In the case of the standard MK46 barrel, the model included only steel; therefore, the Stellite 21 material properties were not used.

Loading. When the MECHANICA FEA model was run in the structural dynamic time mode, the loading included the time-dependent bore and gas block pressures. Moreover, the analysis included a damping coefficient of 20.19%. This damping coefficient was estimated from experimental data of firing a standard MK46 weapon and recording the barrel motion with a high-speed camera.

Dynamic Response. In addition to comparing the structural aspects of the barrel designs, the barrel dynamic response (particularly the muzzle displacement and velocity) estimates and compares accuracy and dispersion for each design. Due to the constraint types used in this model, the muzzle deflections and velocity derive only from the structural deformation of the barrel itself. They do not include contributions from the barrel rigid body motion relative to the receiver, and certainly they do not include contributions from the rigid body motion of the weapon relative to the ground. This approach conforms to the idea of investigating and comparing the structural aspects of three different barrel designs with varying structural characteristics.

The muzzle vertical deflection and velocity quantities that contribute to bullet dispersion occur at about 0.644 ms, just as the round leaves the barrel. The following simple formulae are used to estimate the dispersion at 100 m using these two quantities

$$D_{d100} = \frac{D_m}{R_b} 100000 \quad \text{Dispersion at 100 m due to muzzle vertical deflection}$$

$$D_{v100} = \frac{100000}{V_r} V_m \quad \text{Dispersion at 100 m due to muzzle vertical velocity}$$

where

D_m = Deflection at the muzzle as the round exits the muzzle

R_b = Radius of barrel rotation (=96.5 mm, located before the gas block)

V_r = Round velocity (838.200 m/s)

V_m = Round vertical velocity as the round exits the muzzle

Dynamic Response Results for Standard MK46 Barrel

The dynamic response for the standard MK46 barrel provided information about the muzzle vertical deflection and its velocity, which was used to calculate the contribution to dispersion at 100 m. The dispersion due to the vertical muzzle deflection was 9.020 mm or 0.355 in., and the dispersion due to vertical muzzle velocity was 6.136 mm or 0.242 in. The combined dispersion was estimated at 15.156 mm or 0.597 in. These results will form the base line of the comparison presented in table 3.

It was clear that the structural oscillations from the previous round do not influence the oscillation of the following round, which means that the oscillation effects were not cumulative. This was directly dependent upon the damping coefficient whose value was given as 20.19%. While the damping coefficient used was typical of structural damping, it is important to note that it was also obtained experimentally.

Dynamic Response Results for the Modified MK46 Barrel with Stellite

The FEA model for the modified MK46 barrel with a Stellite insert differs from that of MK46 with Stellite model only in the external geometry. The loading, gas block simulation, materials, and constraints are not changed.

The dynamic response provides information for vertical deflection and velocity at the muzzle, which was used to calculate the contribution to dispersion at 100 m. The dispersions were calculated using the same formulae as in the standard design. The dispersion due to muzzle vertical displacement was 10.783 mm or 0.425 in., and the dispersion due to the muzzle vertical velocity was 6.647 mm or 0.262 in. The combined dispersion was 17.430 mm or 0.686 in. As in the previous two designs, the oscillations in previous rounds did not influence those of the following rounds.

Dynamic Response Results Summary

The dynamic response comparison is summarized in table 3. The overall dispersion of the modified MK46 barrel with Stellite insert was only 15% more than the baseline standard design. Based on these results, the specific geometry in this analysis was used as the final design configuration.

Table 3
Structural dynamic response comparison

Barrel	Standard MK46	Modified MK46 with Stellite	Modified MK46 with Stellite comparison (%)
Maximum deflection (mm)	0.045	0.0499	10.9
Deflection at 0.644 ms (mm)	0.0087	0.0104	19.5
Dispersion due to deflection at 100 m (mm/in.)	9.02/0.355	10.783/0.425	19.5
Maximum velocity (mm/s)	72.15	74.3	3.0
Velocity at 0.644 ms (mm/s)	51.43	55.714	8.3
Dispersion due to velocity at 100 m (mm/in.)	6.136/0.242	6.647/0.262	8.3
Combined dispersion (mm/in.)	15.156/0.597	17.430/0.686	15.0

Note: This information was developed using material properties at room temperature.

Structural Static Analysis

During the firing of a round, the chamber and bore surfaces experience stress calculated to be on the order of 100 ksi. Although these stresses are not large enough to cause the barrel to fail, they do contribute to the gradual erosion of the bore. Ideally, the modified MK46 barrel with Stellite design would not have stresses that exceed the baseline design. This static analysis identifies the areas of high stress by using the FEA models derived earlier. These models were run in the MECHANICA static analysis mode. The geometry, constraints, materials and gas cylinder simulations did not change. However, the loading in the bore, chamber, and the gas block were changed to represent the pressure behind the round in a quasi-static mode. Instead of time-dependent pressures, the maximum pressure value for each bore section, chamber, and gas block were used to obtain 11 distinct static solutions. From these 11 solutions, only three considered critical with respect to stress are presented here.

Standard MK46 Barrel

The following three static analyses investigated the standard MK46 design.

Chamber and Bullet Lead Area. The maximum pressure in the chamber (when the round begins to accelerate) was 329.588 MPa*. The maximum Von Mises stress occurs around the bullet lead area and it was about 650 MPa or 94, 274.53 psi.

Bore 1 Area. Conservatively, the pressure value behind the round was taken to be equal to that of the chamber; e.g., 329.588 MPa. The resulting Von Mises stress, however, was 700 MPa, which was slightly higher than before due to the smaller inner diameter.

Gas Block Area. This static solution is presented here only to show the effects of the gas cylinder pressure acting on the barrel. As before, the pressure behind the round was estimated at 135 MPa. The pressure in the gas cylinder was 12.557 MPa. The resulting Von Mises stress was 300 MPa, which was much smaller than the stress experienced when the round was at the bullet lead.

*For conversion: 1 MPa = 145.038 psi.

MK46 Barrel with a Stellite Insert

The following three static analyses investigated the MK46 barrel with Stellite insert.

Chamber and Bullet Lead Area. The maximum pressure was identical to that of the standard MK46 model. The Von Mises stress distribution due to this pressure was also identical to that of the baseline design. This was not unexpected, since the geometry and the loading of the two designs are identical, and the material properties of the barrel steel and Stellite are very close (table 2).

Bore 1 Area. As in the previous analysis, the Von Mises stress distribution was identical to that of the base line design, due to the fact that the geometry, loading, and constraint conditions were identical. The barrel steel and Stellite material properties were close enough, so that they did not produce a considerable difference in the stress distribution.

Gas Block Area. As in the two previous analyses, the resulting Von Mises stress distributions were identical to those of the baseline design, for the same reasons identified before, namely that the geometry, loading, and constraint conditions were identical, and that the two materials have similar material properties.

Modified MK46 Barrel with a Stellite Insert

The following three static analyses investigated the modified MK46 barrel with Stellite insert.

Chamber and Bullet Lead Area. The maximum pressure was identical to that of the standard MK46 model. The Von Mises stress distribution due to this pressure was also identical to that of the baseline design. This was not unexpected, since the geometry in the chamber area was not changed drastically.

Bore 1 Area. The Von Mises stress distribution was 750 MPa, which was slightly higher than that of the baseline design. This was expected due to the fact that barrel geometry was changed slightly in the process of removing material.

Gas Block Area. The loading and constraints were identical to those of the baseline design. The differences introduced by the Stellite were not significant, since Stellite and the barrel steel have very similar material properties. However, the geometry was changed in the process of removing material. Despite this geometry change, this analysis did not show a significant change in the Von Mises stress distribution. The resulting Von Mises stress was found to be 300 MPa, which was identical to that of the base design.

Static Analysis Results Summary

Table 4 shows the comparison summary of the static stress analyses for the three different barrel designs. As expected, there was no difference in stress levels between the standard MK46 barrel and the MK46 barrel with Stellite. In one region, there was a slight 50 MPa increase in stress in the modified MK46 with Stellite design.

Table 4
Static analysis comparison summary

Barrel design	Standard MK46 (MPa)	MK46 with Stellite 21 (MPa)	Modified MK46 with Stellite 21 (MPa)
Chamber VM stress at 329.59 MPa in the bore	650	650	650
Bore 1 VM stress at 329.59 MPa in the bore	700	700	750
Gas block VM stress at 135 MPa in the bore and 12.56 MPa in the gas cylinder	300	300	300

The overall comparison of stresses shows little to no difference in the respective designs. Given this, it was reasonable to assume that for similar conditions, a barrel's performance was a direct result of its material properties. In short, the new design geometry should not detract from the performance of the Stellite-lined barrel.

Transient Thermal Model

The following portion of the report investigates the thermal characteristics of the barrel. The investigation used ANSYS FEA, which provided a great flexibility with respect to loading functions, contact between surfaces of different parts, boundary conditions, and more importantly, it allowed the use of radiation from irregular surfaces.

Radiation Versus Convection

The issue of the significance of radiation often comes up in barrel design. A simple manual calculation shows that radiation is almost always as important as convection, and when the surface temperature is over 200°C, radiation is much more prevalent than convection. Radiation heat flux and equivalent heat transfer coefficient grow drastically at about 300°C. This implies that adequate definition of radiation behavior and effects is imperative to obtain good data from any FEA model, and consideration of radiation is essential in machine gun barrel design calculations.

ANSYS FEA Model

The following assumptions and considerations were used to generate the ANSYS model.

Geometry. In order to investigate the firing of as many rounds as possible, only a 27-deg sector of the barrel was used. This portion of the barrel does not include the bottom portion of the gas block; however, it was adequate to study the thermal behavior of the barrel. For the case of the barrels with a Stellite insert, the ANSYS model contained contact elements to simulate the effects of the steel to Stellite interface.

Loading. Heat transfers from the hot gas to the bore. This load was represented by the gas temperature, $T(t)$, and the heat transfer coefficient, $h(t)$, both functions of time. These are experimentally obtained functions from the studies of a 25-mm barrel, and they are mentioned in referenced 5. Due to their experimental nature, it is suspected that they incorporate both radiation and convection from the gas to the bore.

Boundary Conditions. The boundary conditions of convection and radiation are applied to the exterior surface of the barrel. The heat transfer coefficient and the ambient temperature are constant [$h = 8 \text{ W/m}^2\text{-C}$ and $T = 25^\circ\text{C}$ (ref. 2)]. Radiation uses an emissivity of 0.95, as measured with an infrared camera for the standard MK46 barrel. The surface radiation form factors for the complex exterior surface of the MK46 barrel were calculated by ANSYS FEA. Heat transfer to the receiver was included in these boundary conditions; however, this portion of the surface could be given different boundary conditions to adjust the flow of heat to the receiver for a better approximation of the real life model.

Materials. Table 5 shows the thermal material properties used in this model. Stellite 21 is included in this table; however, it was not used in the model for the standard MK46 model.

Table 5
Thermal material properties

Material	Density (Kg/m ³)	Specific heat (J/Kg-C)	Conductivity (W/m-C)
Steel	7827.80	473	43.01
Satellite 21	8387.04	423	14.7

Results. Figure 5 shows the temperatures as functions of time at a typical cross-section of the barrel. Each spike on this curve represents a round fired, and there are 50 rounds at the end of each graph (the end of 50 rounds occurs at 4.27 sec). The curve labels "Bore_Temp", "Bore_Vicinity_Temp", "Mid_Point", and "Surface_Temp" represent temperatures at several points along the radius of the barrel. It was noted that the bore temperature oscillates considerably in response to each round fired. At the beginning of firing, this temperature oscillates between 25° and 580°C , and at the end of the 50 rounds, between 410° and 890°C . This oscillation gets less and less obvious for temperatures at points closer to the surface. The solution database for this model can be used to investigate any temperature and heat flux value, at any nodal point of the model in the post-processing mode.

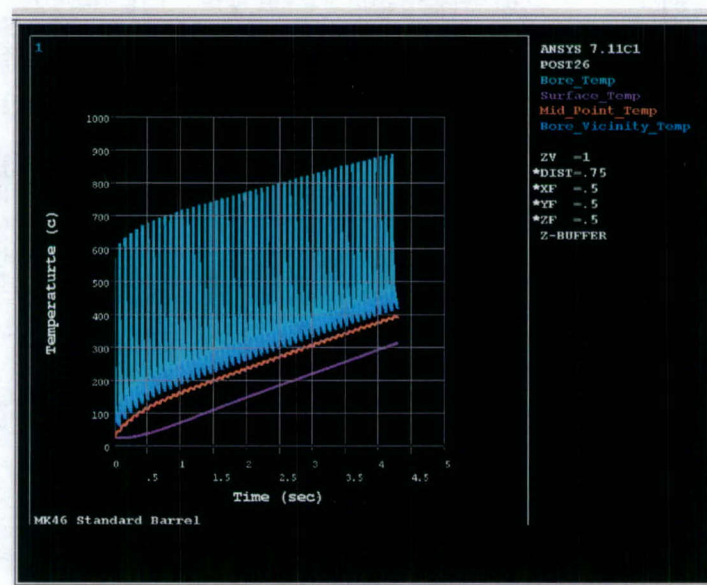


Figure 5
Temperatures

Model Verification. Testing was conducted using an infrared camera to record external barrel temperatures while test firing a 50-round burst. Test results summarized in this report indicate the measured barrel temperature in the fluted region was 160°C at the end of the burst. This experimentally measured temperature was much lower than that obtained with the analytical model.

A detailed review of modeling techniques and assumptions used to develop the analytical model was performed to better understand this discrepancy. The most likely reason for the difference in calculated versus measured barrel temperature was the heat transfer coefficient and gas temperature functions applied to the bore. As stated previously, these functions were obtained experimentally from studies of a 25-mm barrel per reference 5.

It is apparent from the test results that one or both of the experimentally obtained functions was too severe for the 5.56-mm MK46 barrel. However, it was difficult to justify proper boundary condition adjustments necessary to correlate analytical results.

The barrel temperature calculated analytically can be adjusted to match the measured temperature by modifying both the heat transfer coefficient and gas temperature boundary conditions or, by modifying one of the boundary conditions while the other remains unchanged. Any one of these adjustment scenarios can lead to correlation of the barrel outside temperature. However, the temperature distribution through the thickness of the barrel will vary depending on which scenario is chosen. Therefore, matching the external barrel temperature only is not sufficient validation of the analytical approach.

This discussion prompted a decision to discontinue further thermal transient analyses and, instead, rely on physical testing to compare barrel designs. Details of all test results and design comparisons are summarized later in this report.

PROTOTYPE PROCESS DEVELOPMENT AND FABRICATION

FNMI Manufacturing Process

A previous FNMI project developed a methodology to fabricate Stellite-lined M249 barrels. This process was further refined during this effort. An outline of the process is shown in figure 6.

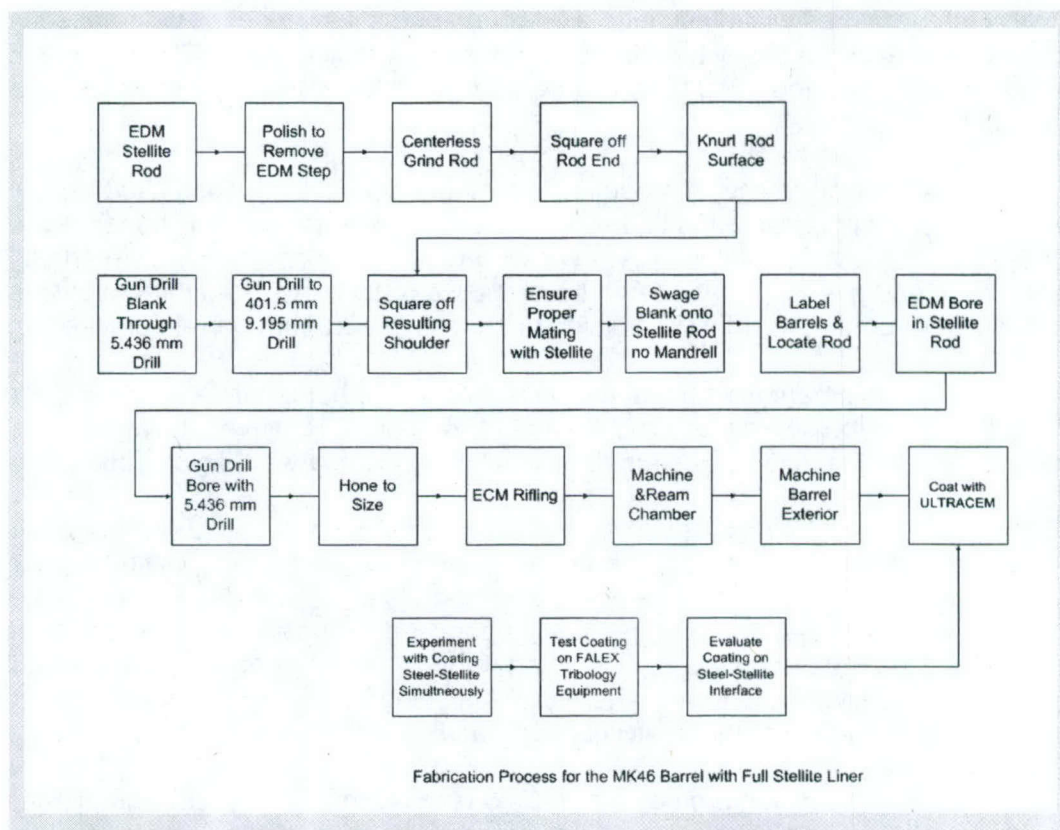


Figure 6
Fabrication process for the MK46 barrel with full Stellite liner

UltraCem Coating Process

The surface characteristics of the Stellite liner were modified by applying UltraCem coating. The UltraCem coating was selected to significantly reduce the bore coefficient of friction, in turn reducing abrasion-type wear. UltraCem reportedly has a strong chemical affinity to Cobalt, the main alloying ingredient of Stellite. It was also expected to form a fine insulating layer that may impede heat transfer into the barrel interior. Less heat transferring into the barrel interior allows additional mass removal, since the mass is no longer needed as a heat sink. Due to the nodular nature of the UltraCem, this layer is very ductile, which makes it ideal for the cyclic type loading encountered inside the barrel.

The prototypes were designed to have the interior and exterior of the barrel tubes coated with UltraCem. Threads on the barrel were masked following a flash-coating to prevent excessive buildup of the coating. The coating was removed in specific areas, such as at the gas block, to allow for match grinding and assembly of the barrel tube and mating components. The remainder of the components were phosphated prior to assembly. The standard high-temperature coating used on the MK46 was not used due to the addition of the UltraCem to the exterior of the barrel.

Because of the unique nature of the Stellite-lined barrel design, considerable development of the UltraCem Nickel-Boride coating was necessary. Universal Chemical Technologies Defense (UCTD) was contacted to determine their ability to deposit UltraCem on Stellite. A significant amount of process development with samples was necessary in order to achieve a coating on the bi-metal system. Unforeseen difficulties were experienced during the initial attempts to coat the barrels, but after investigation and corrective actions were established, the barrels were recoated to the final state.

Though the coating thickness was found to be excessive during barrel measurement, and many of the sample bores and rifling were out of specification, it is believed that some additional coating process development would yield repeatable barrels that are dimensionally within specifications. At the very least, it was proven possible to coat the bi-metallic system. Given time and additional samples to work with, it should be possible to tweak the process to achieve the correct coating thickness.

PROTOTYPE HARDWARE TESTING AND RESULTS

Barrel Weight

The prototype MK46 Stellite barrel design was found to be 2.1 lbs. A standard MK46 barrel was weighed for comparison and was measured to be 2.35 lbs. The total reduction achieved was 0.25 lbs, or approximately 11% relative to the MK46 baseline barrel and 48% relative to the M249 standard barrel.

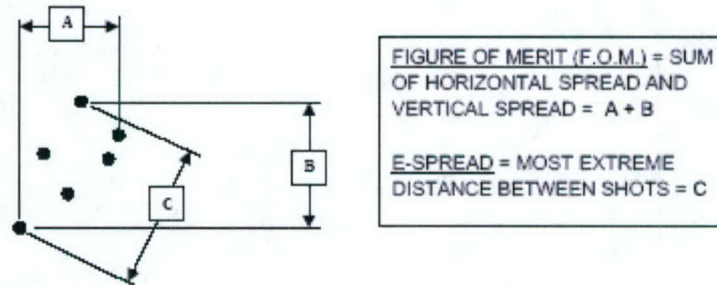
Functional Testing

For safety reasons, every barrel was subjected to high pressure proof testing. In addition, five barrels were tested for targeting, accuracy, and muzzle velocity. Due to bore and rifling dimensions not being correct, it was expected that these data points would be out of specification. The barrels used in these tests were numbers 4, 7, 8, 9, and 12. Test results can be found in table 6. The figure of merit for all barrels was higher than that of the baseline MK46. This accuracy error was attributed to the bore and rifling being incorrect due to the error in coating thickness, and especially due to the taper out towards the muzzle end. The muzzle velocity also suffers due to the large bore and rifling. The average muzzle velocity was approximately 76 ft/s below the baseline MK46 barrel. All functional testing was performed using the same weapon, except for changing the barrel.

Table 6
Functional test results

Barrel no.	Figure of merit (cm)	E-spread (cm)	Average muzzle velocity (ft/s)
Standard MK46	19.4	10.5	2874
4	37.4	22.8	2812
7	47.3	23.8	2810
8	29.3	18.4	2764
9	33.9	25.3	2803
12	22.4	15.1	2802

Table 6
(continued)



Barrel Deflection

The original plan was to measure barrel deflection using accelerometers. There was an excessive amount of noise in the data, which made it difficult to determine displacement. High-speed video was used instead. Since the high-speed video camera does not have to attach to the barrel, the data was free of noise. The video was recorded at 100,000 frames per second. The video was then analyzed with motion analysis software. The results from this test were considerably better than that of the accelerometers.

Figures 7 and 8 show the measured muzzle displacements of the baseline and Stellite-lined barrels, respectively. The approximate exit time of the bullet from the muzzle is represented by the vertical line on the figures. The muzzle displacements of the MK46 and the Stellite MK46 barrels were 1.15 and 1.3 mm, respectively. This is a 13% difference between the two barrels.

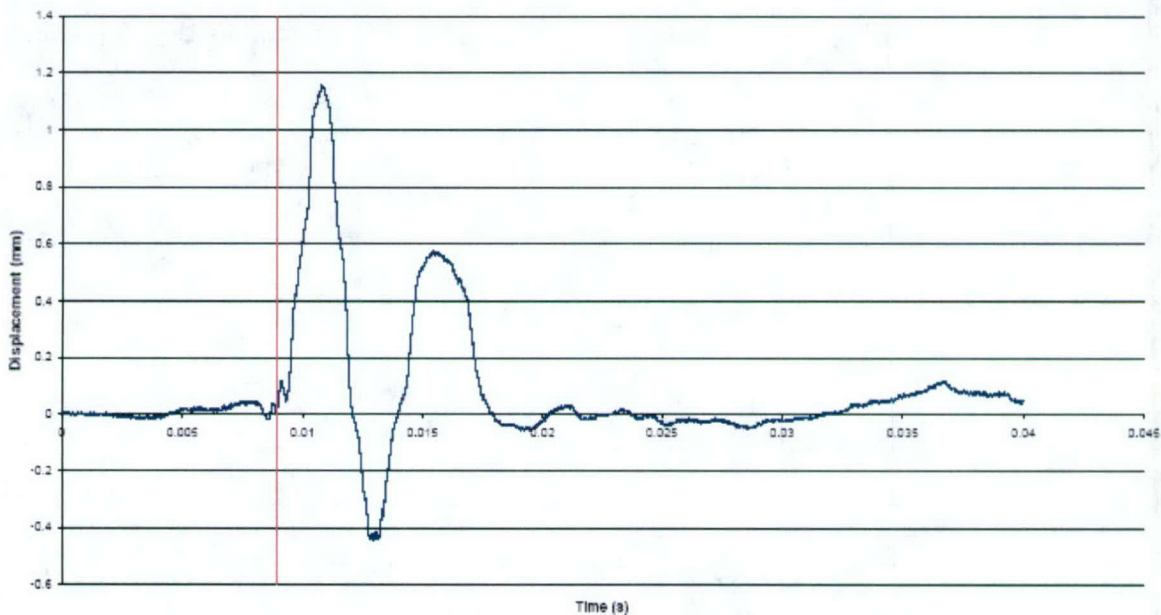


Figure 7
MK46 baseline barrel muzzle displacement

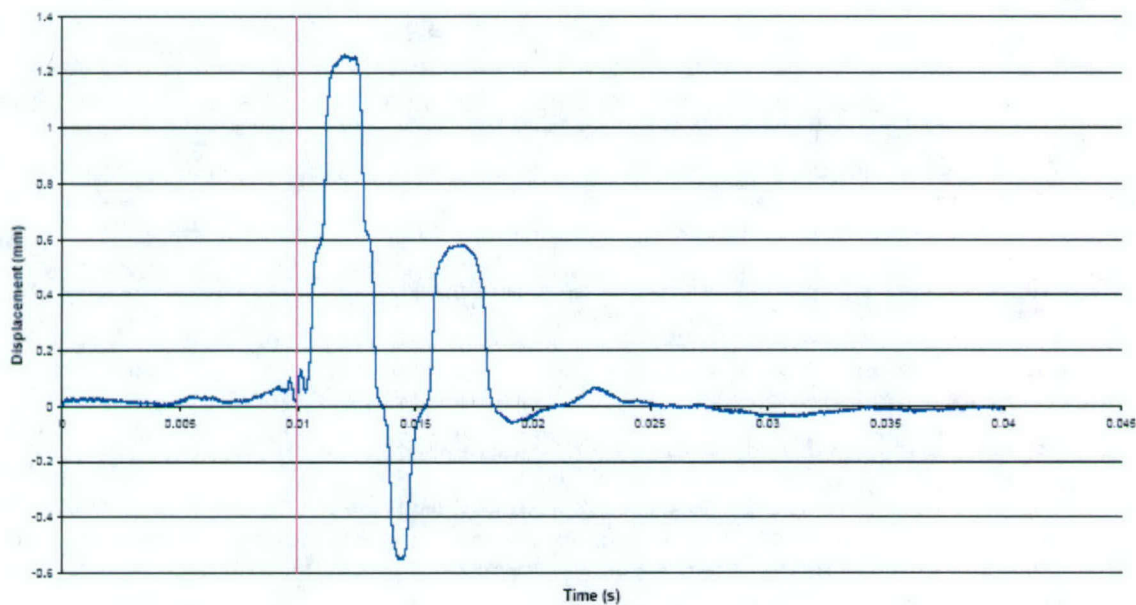


Figure 8
MK46 stellite barrel no. 1 muzzle displacement

The maximum displacements shown in the figures are much greater than that calculated in the structural analysis. The structural analysis showed a maximum displacement of the MK46 and Stellite MK46 barrels as 0.045 mm and 0.050 mm, respectively, for an 11% difference between the two barrels. The structural analysis used a constraint on the nozzle of the gas block to represent the gas tube interface. In the analysis, the nozzle was allowed to move in and out of the gas tube, but was restrained in the other two directions. The actual assembly has a gap that allows for a small amount of unrestrained vertical motion that was not accounted for in the analysis. The structural analysis shows deflection due to the bending of the barrels and the gas tube. It does not account for the relative motion of the barrel to the receiver. This was the reason for the measured values not being consistent with the structural analysis. However, the ratio of maximum deflections between the barrels was consistent for the structural analysis and high-speed video measurements. Furthermore, in comparing the curves of the structural analysis and the measurements, it can be seen that the damping used in the analysis was accurate. Both graphs show the motion damping out in approximately 0.010 sec. It is reasonable to assume that the analysis provides a valid qualitative approximation to the actual system response.

Drop Test

One Stellite MK46 barrel was drop tested using a M249 weapon platform. The gun was dropped with the gun vertical barrel down and with the gun at 45 deg barrel down. The barrel was then inspected for cracks and checked for straightness. Twenty rounds were then fired through the barrel to check function. The barrel functioned properly and all applicable post-test measurements were compliant.

Thermal Test

As discussed in the Transient Analysis Model Verification section of this report, the analytical results from the thermal model that was developed did not correlate well to the empirical data that was collected for the MK46 barrel. The numerous variables that can affect the results make it difficult to determine the proper boundary conditions. To better understand the effect of the Stellite liner on the barrel, a thermal imaging camera was used to collect temperature data on several barrel configurations.

Thermal data was collected on M249, M249 Stellite, and MK46 barrels. The barrels were tested by firing continuous bursts of varying duration. The M249 and M249 Stellite barrels showed very similar temperatures for each firing schedule. The temperature of the MK46 barrel was substantially higher than that of the M249. This increase was due to the smaller amount of mass in the MK46 barrel. Since the addition of the Stellite liner had little effect on the exterior barrel temperature on the M249 barrel, no significant change to the MK46 barrel temperature was anticipated due to the Stellite liner. However, it was expected that the MK46 Stellite barrel would show an increase in temperature over the standard MK46 due to the removal of mass. A prototype MK46 Stellite barrel was tested by firing a 50-round continuous burst, and the temperature data was recorded using thermocouples. It can be seen in figure 9, that the temperature was indeed slightly higher for the MK46 Stellite barrel.

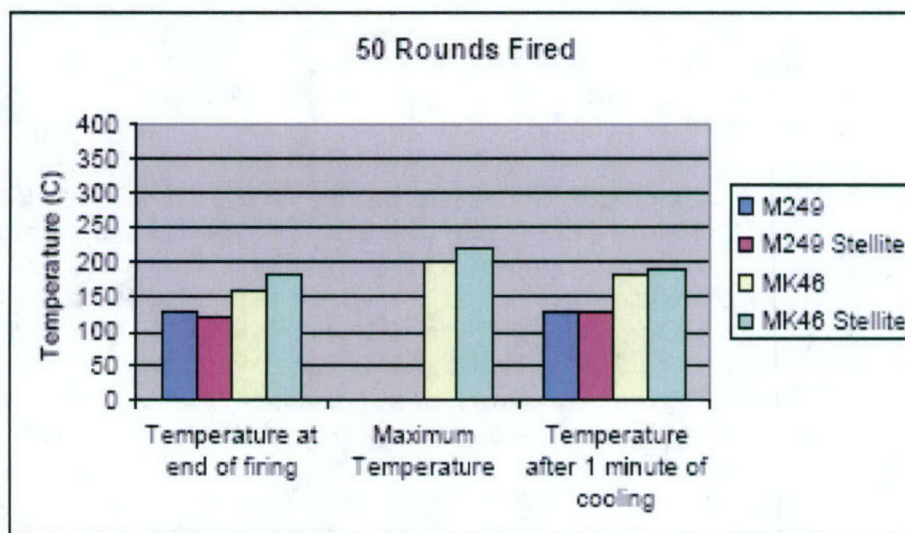


Figure 9
50 rounds fired

CONCLUSIONS AND RECOMMENDATIONS

The program objective was to reduce the weight of the 5.56-mm M249 barrel. The weight reduction was attained using the MK46 barrel as a baseline, and implementing the use of a full Stellite liner with state-of-the-art UltraCem nickel-boride coating. Optimization of the barrel contour was accomplished using a variety of analytical methods prior to fabricating prototype barrels for testing.

A modified MK46 barrel lined with Stellite 21 was optimized to take advantage of the fact that Stellite can retain its mechanical properties at much higher temperatures than those of the standard M249 barrel steel. The optimized barrel design reduced the weight by approximately 0.25 lbs. or 11% relative to the MK46 baseline barrel and 48% relative to the M249 standard barrel.

By focusing in large part on the theoretical and experimental analysis of the barrel, it was expected that the actual test results would be approximately those determined through analysis. This procedure was intended to have limited the amount of part iterations and testing.

Some live fire testing was conducted. Five of the 10 prototype barrels were shot and test data was collected for functional tests, dynamic motion measurements, and thermal evaluations. In some limited areas, conclusions could be made from the data that was collected. Relative to the structural aspects, the empirical data provides support of the analytical results obtained during the barrel optimization and analysis efforts. These results indicate that the MK46 barrel can be successfully lined with Stellite 21 without adverse consequences to the barrel's modal frequency response.

Additionally, results indicate that the temperature response, after lining the barrel with Stellite 21 and having removed mass from the exterior of the barrel, can be roughly predicted analytically, given that the proper coefficient inputs are known. These inputs may initially need to be determined experimentally, but should be valid for theoretical use from that point. Temperature measurements of in-process barrels indicated a slight increase in temperature for the Stellite-lined barrels over a standard production barrel.

Difficulties encountered during the UltraCem application process resulted in bore and rifling dimensions tapering oversize, which had a significant effect on the accuracy and muzzle velocity of the barrels. All barrels are expected to have high figure of merit and E-spread values, and low muzzle velocities. This exercise has proven it is possible to coat the bi-metallic system with Stellite 21 and steel. It is very likely that further process development effort would have soon yielded dimensionally-correct barrels that would be competitively accurate as compared to present standard production barrels.

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10630 Little Patuxent Parkway, Suite 202
Columbia, MD 21044-3204

GIDEP Operations Center

P.O. Box 8000
Corona, CA 91718-8000

FN Manufacturing, Inc
797 Old Clemson Road
Columbia, SC 29229