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Cylindrical Magnetron Sputtering (CMS) of Coatings for Wear Life Extension in Large Caliber Cannons

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Cylindrical Magnetron Sputtering (CMS) of Coatings for Wear Life Extension in Large Caliber Cannons

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ABSTRACT

For tank cannons, the battlefield demands for increased muzzle velocity and lethality have resulted in wear life reduction of the barrel. Cylindrical magnetron sputtering is being developed as a new, environmentally friendly bore coating process for large caliber cannons. This paper discusses how, in general, the process is being applied and describes how technology maturation is being achieved. Obtaining acceptable adhesion has been the greatest technical challenge encountered. Specific enabling technologies to improve coating adhesion are discussed.

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INTRODUCTION

For tank cannons, the battlefield demands for increased muzzle velocity and lethality have resulted in the development of propellant formulations that decrease the wear life (more accurately described as erosion life) of the barrel. The barrel has 120mm diameter, contains a smooth bore (rather than a rifled bore), is made out of an ASTM A723 Grade 2 steel similar to AISI 4335V, and is approximately 5.3 m long. The M829A3 kinetic energy round is currently the most erosive round used in tank cannon. When exclusively using this round, the erosion life of the gun barrel ranges from 180 to 375 rounds depending on round conditioning temperatures [1]. This is only a fraction of the fatigue life of the barrel.

The environment that the bore of the gun barrel experiences during firing can only be described as tortuous. The firing environment is highly transient in nature; in a matter of milliseconds the firing cycle has been completed. During the firing cycle, the bore of the gun barrel experiences a pressure pulse of up to 700 MPa and an accompanying thermal pulse which can exceed 1400C. Over its life, the gun barrel experiences these conditions for only a few seconds before it is condemned due to erosion. Consequently, investigating the erosion phenomena in gun barrels has received renewed interest over the past few decades [2-4]. After much spirited debate in the Army technical community, there is now a general consensus as to the predominant damage mechanisms in large caliber tank cannon erosion. The transient thermo-mechanical pulse from tank cannon firing results in the formation of enormous *local* compressive stresses in the bore of the gun barrel. If adhesion of the bore coating is poor, the coating will spontaneously buckle due to these transient thermo-mechanical stresses. The transient compressive stresses exceed both the yield strength of the coating and of the near-bore steel substrate, and result in the formation of tensile residual stresses after the firing cycle has been completed. These tensile residual stresses cause the commonly observed heat check cracks (also referred to as craze cracks, mud flat cracks, and permafrost cracks).

Depending on the bore coating thickness, strength, and ductility, these heat check cracks may or may not extend to the coating/substrate interface. The presence of these cracks, particularly those wide cracks that terminate at/near the interface, result in the generation of large shear and peeling stresses in the coating in subsequent firing cycles [5-6]. The presence of heat check cracks that extend to the interface also results in exposure of the susceptible steel substrate to the aggressive chemical species in the propellant, namely carbon dioxide (CO₂), carbon

monoxide (CO), and hydrogen sulfide (H₂S), and the subsequent formation of low melting point iron reaction products [1, 3]. This preferential thermo-chemical attack of the steel undermines the coating and increases the likelihood for subsequent coating loss. In the current tank bore coating, high contractile electroplated chromium (HC Cr), once an island of coating is removed due the above mechanisms (described as micropitting in the Army technical community), the convection coefficient is increased due to increased turbulence within the micropit. This results in higher local temperatures and stresses and accelerates the erosion process [1].

Obviously, a bore coating that is well adhered, resilient to thermal shock cracking, and which exhibits a low crack density, will result in an improvement in tank cannon erosion life. Circa 1980, tantalum was selected as a candidate replacement material for the current HC Cr coating due to its high melting temperature, inherent ductility and toughness, thermal shock resistance, and its excellent performance in previous firing tests on 20mm and 105mm barrels [2, 7]. Unfortunately, the process used to deposit these tantalum coatings (electrodeposition from fused salts) could only be performed at high temperatures (800C) and compromised the heat treatment and mechanical properties of the steel substrate. In tank cannons, the swage autofrettage process is used to impart desirable compressive residual stresses in the gun barrel. This results in a lighter weight barrel that can withstand the high pressures of the firing cycle without yielding. A secondary benefit is an enhanced fatigue life. These beneficial autofrettage stresses are severely compromised once bulk temperatures in the barrel exceed approximately 350C.

CYLINDRICAL MAGNETRON SPUTTERING (CMS)

Cylindrical magnetron sputtering (CMS) is a scalable process technology that can be used to deposit a multitude of high performance materials and alloys at low process temperatures (<350C) without the generation of any hazardous wastes [9, 10]. Tantalum and chromium coatings have been deposited on short section 120mm gun barrels with coating thickness ranging from approximately 70 microns to 325 microns and at deposition rates of approximately 14-18 microns/hour.

CMS is a physical vapor deposition process in which the material to be deposited (also known as the target material or cathode) is bombarded by energetic ions, subsequently vaporized, and is ejected through a low pressure vacuum environment at energies on the order of 1-10 eV to the substrate, upon which the

material condenses, nucleates, and grows into a coating. Figure 1 shows a schematic of the CMS process for large caliber cannons. For our application, the gun tube itself is used as the vacuum chamber. A target assembly is aligned along the centerline of the gun barrel. This assembly consists of the tubular target material (e.g. Ta), ceramic end components to hold the target in place and to electrically isolate the target, a copper pipe onto which the target and ceramic components are attached, and an array of samarium cobalt magnets which enable magnetron operation. Water flows through the copper pipe to cool the magnets and to provide some radiational cooling of the target during operation since there is no contact between the target and the copper pipe.

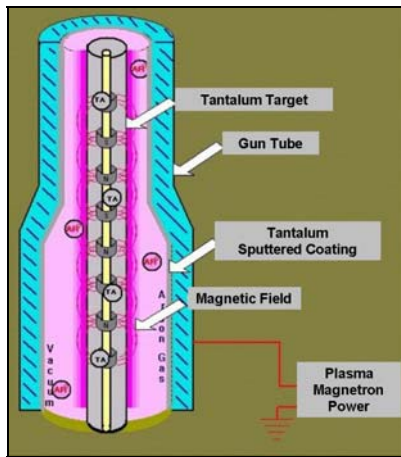


Figure 1. Schematic of CMS process for large caliber gun barrels.

During sputter deposition, the entire gun barrel section is coated at the same time; the area to be coated is controlled by the length and placement of the magnet array. The magnets are oscillated in order to provide uniform erosion of the target material.

Figure 2 shows a solid model of the target assembly within the CMS platform. Clamshell heating/cooling bands are placed along the barrel section in order to facilitate bakeout and to control the substrate temperature during operation. A series of roughing pumps, turbo-molecular pumps, and water traps are used in concert to achieve a low base pressure, typically on the order of 10^{-8} torr. After bakeout, a novel in-situ plasma cleaning device (PCD) is translated within the vacuum chamber to clean both the target and substrate in order to remove the native oxide and other surface contaminants [10]. This PCD is then docked within the system and the sputter deposition process is commenced. Either argon or krypton sputtering gas is used during sputter deposition, depending on the coating properties desired. A typical magnetron voltage of approximately -500V is applied between the target and substrate and results in ionization of the sputtering gas. The positively charged ions are electrically attracted and collide with the more negative target, analogous to “atomic billiards”. These target atoms are ejected and transported to the substrate upon which they then condense, nucleate, and grow. The interrelationship of magnetron sputtering parameters such as pressure and temperature on coating density and morphology has been thoroughly investigated and is now typically referred to in the Thornton Diagram [11-13].

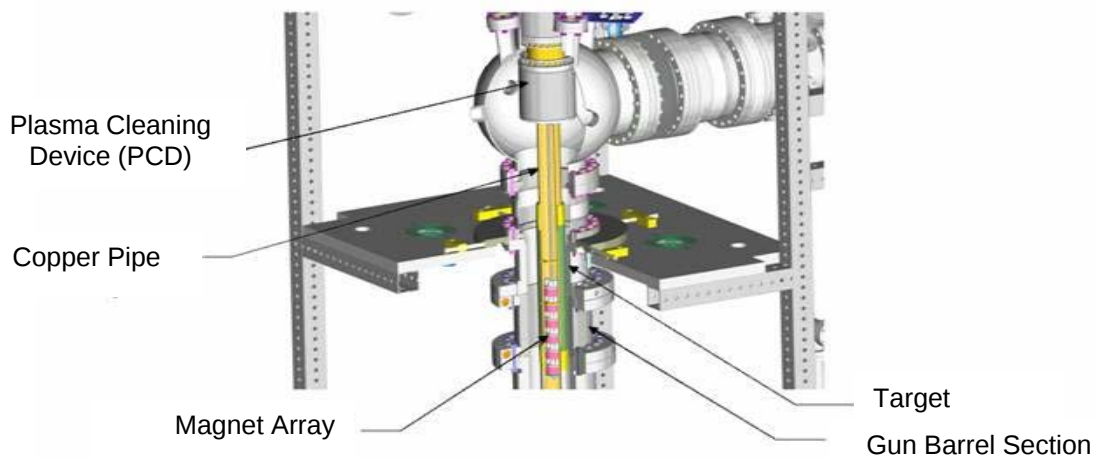


Figure 2. Solid model showing the target assembly and plasma cleaning device within the CMS platform for short section gun barrels.

CMS PROCESS DEVELOPMENT FOR LARGE CALIBER GUN BARRELS

In order to mature CMS process technology for large caliber gun barrels, several sputtering platforms are used (Figures 3-5). Research studies and preliminary concept demonstrations are performed on a planar magnetron sputtering system. Examples of research activities include plasma cleaning, pulsed sputtering, and alloy sputtering. The PMS platform uses a two inch diameter torus style sputtering gun positioned above a platen specimen holder (Figure 3). Three such guns are mounted vertically in the chamber. One gun is dedicated to plasma cleaning the sample substrate and another is dedicated to sputter deposition. After plasma cleaning, the platen is rotated underneath the sputtering gun for coating deposition. Successful concept demonstrations in the PMS platform are transferred to CMS platforms for short section barrels for subsequent technology development.

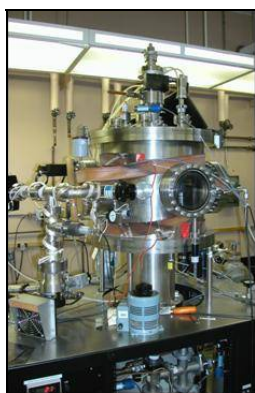


Figure 3 – Planar Magnetron Sputtering platform

In these developmental CMS platforms, thin film depositions are performed on 60mm radius coupons as a screening test prior to thick depositions on 0.3-1.0 meter long 120mm gun barrel sections in order to optimize process parameters (Figure 4). Details of these sputtering platforms are described elsewhere [9, 10]. A rigorous in-house coatings characterization protocol is used to evaluate the integrity and performance of the coatings including laser scanning confocal microscopy, microhardness, scanning electron microscopy, energy dispersive spectroscopy, x-ray diffraction, instrumented microscratch testing, groove testing, laser pulse heating, and vented erosion simulator firing [8]. When warranted, 0.6 meter liners can be fabricated out of 1.0 meter long coated barrel sections, inserted into a full-length tank gun via a heat-shrink process, and fired with erosive

ammunition in order to provide an interim validation of service performance.



Figure 4 – One of two Cylindrical Magnetron Sputtering platforms for short length, large caliber gun barrels.

A full-length pre-production CMS Platform is currently being completed at the Watervliet Arsenal, Watervliet, NY (Figure 5). This platform will be able to coat full-length 120mm and 155mm cannons and will be used to ensure that the manufacturing processes are robust and reliable prior to production. The final validation for the process shall be a CMS coating deposited in the erosion zone of a full-length, lightweight 120mm gun and test fired with erosive ammunition. The erosion zone in the tank barrel extends from approximately 0.9 meters to 2.6 meters from the rear face of the tube (RFT) depending on the ammunition fired. The primary objective of this validation test is to extend the erosion life of the barrel by approximately 50%.



Figure 5 – Full-length, pre-production Cylindrical Magnetron Sputtering Platform for large caliber gun barrels.

DISCUSSION – Coating Adhesion

Coating adhesion remains the greatest technical challenge that is impairing the further scale-up and maturation of the CMS process. Efforts to improve adhesion included early plasma cleaning studies followed by the development of a patent pending plasma cleaning device (PCD) to provide oxide free target/substrate surfaces prior to sputter deposition, the use of an interlayer between the Ta coating and steel substrate, the use of energetic bombardment through pulsed DC sputtering, the development of aggressive vented erosion simulator (VES) testing to assess improvements in adhesion, and the use of various barrel surface preparation processes prior to in-situ plasma cleaning.

Plasma Cleaning and the Development of a Plasma Cleaning Device (PCD)

Early PMS depositions of tantalum on copper without in-situ plasma cleaning resulted in spontaneous delamination of the coating due to high intrinsic stresses coupled with poor coating adhesion. In subsequent tests, these depositions were allowed to proceed after delamination. The in-situ delamination resulted in exposure of an oxide free copper surface to the arriving tantalum atoms and resulted in a tenacious metal-metal bond between these two dissimilar metals. This experiment was used as a demonstration of the effectiveness of removing the native oxide from the substrate and provided the impetus for subsequent in-situ plasma cleaning studies. In-situ plasma cleaning has been widely demonstrated to result in improved coating adhesion [14-16].

Prior to the development of a patent pending plasma cleaning device for CMS depositions, the target and substrate material was plasma cleaned onto long copper tubes that were subsequently removed from the vacuum system. Unfortunately, this resulted in breaking vacuum and exposing the substrate to possible re-contamination from water vapor and other sources. Consequently, a plasma cleaning device (PCD) was developed. This device resides within the sputtering system and translates along the target in order to sputter clean both the target and gun barrel substrate. When plasma cleaning has been completed, the PCD is stowed above the gun barrel section and does not interfere with the sputter deposition process [10]. Figure 2 shows a solid model of the PCD within the CMS platform. Recent improvements in the PCD have contributed to significant improvements in coating adhesion.

Interlayers

In order to improve adhesion and try to promote the more ductile, tough, and thermal shock resistant alpha tantalum phase, interlayers such as niobium and chromium have been investigated. It was demonstrated that niobium was extremely potent at promoting alpha tantalum, likely due to the similarity in the crystal structure and lattice parameter. However, it was determined that niobium was too susceptible to both oxygen and hydrogen to be considered a viable interlayer candidate. Use of a 10 micron thick CMS Cr interlayer has been repeatedly demonstrated to improve coating adhesion through a variety of in-house testing from microscratch to vented erosion simulator testing. Testing has demonstrated that Cr is a better promoter of alpha Ta than our gun steel (alpha Fe), though it is far less effective than Nb.

The use of chromium as an interlayer material between Ta and steel is logical since Cr has roughly the same atomic size as iron, is more soluble in iron than Ta, has been demonstrated to intermix with Fe at low process temperatures [17], and does not react with the steel to form a low melting point eutectic as other potential interlayer materials such as niobium ($T_{eu}=1373C$) and titanium ($T_{eu}=1085C$) [18]. The use of a Cr interlayer has also demonstrated to provide enhanced adhesion between the Ta and the Cr compared to the Ta to the steel. This may be related to the similar coefficient of thermal expansion of both metals [19] leading to lower thermal misfit stresses.

Energetic Bombardment

It is well known that the use of energetic bombardment of a growing coating can suppress columnar growth, promote purer coatings, and improve adhesion [11-13, 20-23]. One method of bombardment is through the use of reflected neutrals (e.g. sputtering Ta in Ar) which reflect off of the target and apply significant energy to the substrate and growing coating. Another method is through ion bombardment.

Ion bombardment is introduced in magnetron sputter deposition through application of a negative substrate bias in order to attract the positive sputtering gas ions. These positive ions result in forward scattering (“atomic peening”) and re-sputtering of columnar and nodular regions of the coating, respectively, thereby increasing coating density. During energetic sputtering, weakly bound impurity atoms are preferentially sputtered and result in purer coatings. Reducing impurity levels such as oxygen at the coating/substrate interface promote the formation of a metal-metal bond and will increase coating adhesion. It has also been demonstrated that the localized heating of the substrate from energetic

bombardment results in an increase in interdiffusion rates at heterogeneous interfaces by several orders of magnitude [22]. This mixed or graded interface is believed to result in a higher level of adhesion compared to an abrupt interface.

Biasing technology was not pursued early-on in the CMS technology development, in part because of potential difficulties and complexities in trying to sputter coat the full length of a high aspect ratio 120 mm tube (5.3m long) at once with application of a bias. When it was apparent that adhesion of the CMS coatings needed significant improvement, utilization of cyclic bias sputtering through pulsed DC sputtering was pursued.

Though historically pulsed DC sputtering has been used in reactive sputtering to prevent target contamination by the reactive gas (“poisoning”), the cyclic biasing of the substrate has been reported to produce substantial ion bombardment during deposition [24, 25]. This aspect of pulsed sputtering was exploited in order to try to promote improved adhesion through impurity ejection and interfacial mixing. Figure 6 shows a schematic of the effects of pulsed sputtering on the coating. The three parameters which control pulsed sputtering are the frequency, the duty cycle, and the reverse recovery

voltage (RRV). The frequency determines the number of reversals per second, the duty cycle determines the percentage of time when traditional sputtering of the target is taking place, and the RRV determines the magnitude of the bias. Thin Ta films (5 microns thick) deposited at 50 kHz, with a 80% duty cycle, and a 10% RRV resulted in an approximate 10-15 percent increase in thin film adhesion as measured by instrumented microscratch testing. Incorporation of pulsed sputtering in numerous subsequent thick coatings (ranging in thickness from 105 microns – 225 microns) has been performed. However, it is apparent through vented erosion simulator testing that the adhesion issue, albeit less severe, is still present. Though further improvements in adhesion from pulsed DC sputtering are likely achievable through use of a higher frequency and RRV, and a lower duty cycle, it is unlikely that the benefits from this technology will ever approach that achieved through a traditional, continuous bias. This is because the ratio of bombarding ions to the depositing flux is much lower in the case of pulsed sputtering and the actual ion bombardment does not occur simultaneously with deposition as is the case with traditional biasing.

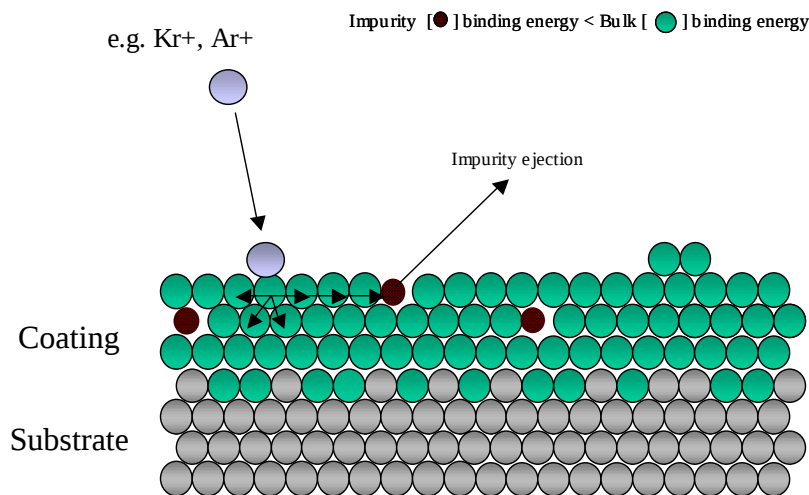


Figure 6. Schematic of the effects of pulsed sputtering on the growing coating.

Barrel Surface Preparation

Early CMS coating depositions on 25mm internal diameter gun barrels utilized grit blasting with glass beads to prepare the tube surface. However, it was found that media could embed itself in the substrate and promote poor adhesion. Moreover, the non-uniform surface promoted shadowing effects, nodular defects, and the undesirable beta tantalum phase. Subsequent tests on 120mm gun barrels utilized honing to prepare the

surface prior to in-situ plasma cleaning. However, the honing marks were considerably deeper than the material removed during the plasma cleaning process. These honing marks served as stress concentrators and failure initiation sites for the sputtering coating. This was highly evident during vented erosion simulator testing (Figure 7). Cracking would immediately occur along these honing marks followed by uplifting and spallation of the coating. Subsequent barrel preparation techniques include the

use of chemical treatment methods to mitigate the honing marks on the tube bore. This is followed by a gentle rotary abrading in order to remove any residue and to improve the surface finish of the bore. This process change has resulted in a significant improvement in coating adhesion as evaluated by both vented erosion simulator and live-fire liner testing.

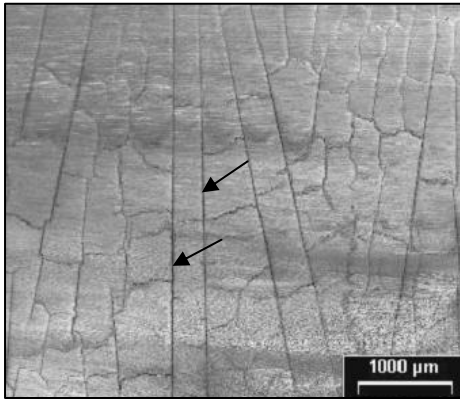


Figure 7. Surface image of sputtered coating after Vented Erosion Simulator testing. The arrows denote the preferential cracking in the coating along pre-existing honing marks in the steel.

Vented Erosion Simulator (VES) Testing

As the quality of CMS coatings improved, rudimentary tests such as groove testing were no longer valid means to assess adhesion improvements. Therefore, more representative tests such as laser pulse heating and vented erosion simulator testing were established [8]. The VES provides the best in-house assessment of coating performance as it closely replicates the firing environment of a large caliber tank gun in the location of worst erosion [4]. A chord from a CMS coated 120mm barrel gun section is precisely fitted to a converging/diverging nozzle (Figure 8). The muzzle face of the nozzle assembly contains a counterbore to hold a burst disk. The burst disk is used to contain the pressure up to approximately 85 MPa in order to promote a more complete burn of the propellant. The VES uses a propellant very similar to that used in the most erosive rounds for the 120mm tank gun, creates a pressure of 275-310 MPa, and nearly duplicates the time at temperature, thereby inducing similar thermo-mechanical shock effects. Further improvements to the VES that are currently being evaluated include increasing the pressure to near peak 120mm firing pressure, utilization of a contiguous ring or hoop of material, and use of a slug material to simulate the transient thermal and mechanical effects of projectile passage. Figure 9 shows how specific CMS process improvements have resulted in significant improvements in coating adhesion as measured by VES performance.

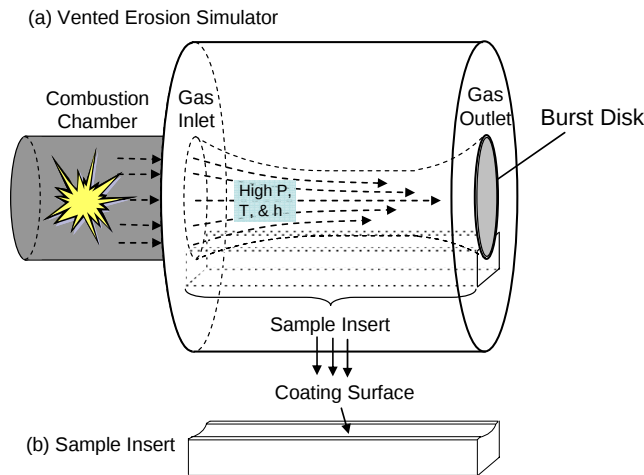


Figure 8. Schematic of: (a) VES and (b) VES test coupon taken from a chord of a 120mm barrel section

SUMMARY

Cylindrical magnetron sputtering (CMS) to deposit refractory metal bore coatings is being developed by the Army in order to extend the life of large caliber cannons. The environment in a large caliber gun barrel, particularly in a tank gun barrel, is highly transient in nature and extremely aggressive. Tantalum has been chosen as a potential replacement bore coating material due to its ductility, toughness, thermal shock resistance, and previous performance in firing testing. CMS has been chosen because it is a scaleable technology, is environmentally friendly, and, most importantly, can deposit tantalum and other refractory metals and alloys at low process temperatures that do not compromise the beneficial autofrettage stresses in the barrel.

Currently thick coatings are being evaluated in 0.3 – 1.0 m long sections of 120mm gun barrels. Coating adhesion has been the greatest technical challenge hindering further CMS technology

maturation. Development of more aggressive and representative adhesion tests was paramount as coating adhesion levels improved. Use of a vented erosion simulator is currently the best laboratory test to currently available to evaluate coating adhesion for large caliber gun barrels. Utilization of chemical and mechanical processes to mitigate honing marks in the bore of the gun barrel, plasma cleaning device improvements, and a DC pulse sputtered 10 micron sputtered chromium interlayer have resulted in significant improvements in coating adhesion.

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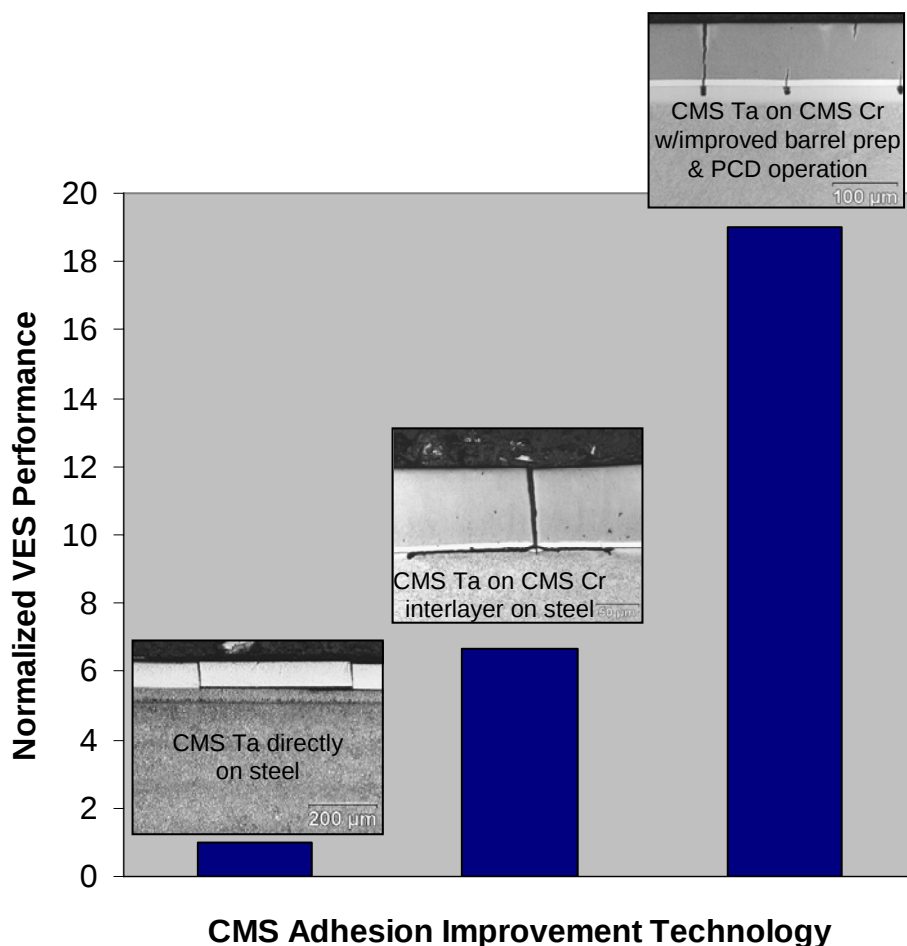


Figure 9. Effect of CMS technology improvements on VES performance with accompanying metallographic images showing typical coating behavior.

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