05CV-38

Surface Mineralization as an Alternative to Cadmium Plating and Hexavalent Chromate Treatment for Corrosion Protection

Nancy Heimann
Elisha Technologies Co., L.L.C.

George T. Simpson
US Navy (ret)

ABSTRACT

The purpose of this paper is to examine the use of a surface mineralization process for general corrosion protection. More specifically, this paper describes the use of surface mineralization (SM) as a non-hazardous and environmentally benign alternative to cadmium plating and hexavalent chromate treatment for protecting fasteners from corrosion in off highway applications.

An engineered surface is founded on a mineral-based product that forms a thin metal silicate surface fully involving the substrate metal.

Completed laboratory cyclic testing of SM treated fasteners compared with cadmium plated and hexavalent-chromate treated fasteners to 180 cycles using the GM 9540P protocol have demonstrated a significant increase in corrosion resistance of components protected by the SM process.

INTRODUCTION

Corrosion, especially crevice corrosion, continues to cost the transportation industry billions of dollars annually. According to a study by Koch et al (2001) the cost of corrosion in the transportation sector is $29.7 Billion per year. In citing that study, the GAO (2003) stated that the direct cost of vehicle corrosion is $23.4 billion per year.

The information presented in this paper is a follow on from the work done by Heimann (2001) in reporting on the development of a cathodically deposited mineral coating as a replacement for hexavalent and trivalent chrome. It is based on the GM 9540P test results reported by Heimann and Soucie (2003).

New techniques that enable an environmentally benign cathodic conversion of a microscopically thin barrier of silica involving the substrate on fasteners show significant results in stopping general corrosion. An older technique of creating a similar silica conversion barrier by delivering mineralizing chemicals to surfaces in a gel has proven effective in stopping general and crevice in a wide variety of applications.

Mineralization technology is the process of forming a thin mineral film on the surface of metals used as protection, decoration, insulation, thermal barrier, primer for topcoats, and other untapped applications. Zinc and ferrous surfaces are mineralized for corrosion control by chemicals delivered to those surfaces by synthetic lubricants, gels or tapes. Current marine applications of this technology for corrosion control include the use by the U.S. Navy of one of the mineralizing gels to protect anchor chain detachable link cavities, application of the mineralizing lubricant to protect weather deck watertight and airtight door dogging mechanisms, cargo doors on the DDGs, and CV/CVN/LHD aircraft elevator wire ropes.

Surface mineralization technology offers a superior performing replacement for undesirable heavy metals such as chromium (e.g., hexavalent chromate), cadmium and lead-based products to provide corrosion protection to fasteners without escalating maintenance costs. The surface mineralization corrosion protection system is not a coating in the conventional understanding of the word. Rather, the mineralization process is a conversion at the molecular level of the naturally occurring surface compounds of oxides and hydroxides to a silicate. The mineral is chemically bonded to the metal substrate. Hence the resulting mineralized surface is not a coating that can be lifted or undermined as a coat of paint may be.

Tapes containing the surface mineralizing chemicals are used to protect the exterior surfaces of pipes carrying fluids up to 425 degrees F from corrosion under insulation.

The development team successfully developed an electrolytic surface mineralization (ESM) corrosion resistant coating process based on silicate chemistry.

Among the advantages of the process are:

- The solutions and rinse waters are environmentally benign.
- The process forms an amorphous smooth surface that exhibits corrosion protection, topcoat adhesion improvement, and greater lubricity.
- The electrolytically applied material has been shown to be a barrier to hydrogen.

Much of the success of the ESM surface chemistry can be attributed to the reaction mechanism. This mineral reaction mimics chemistries found in nature and is tailored to metal finishes. The process creates a tightly adhering interface between the metal and silicate by binding the silicate components with the metal ions from the substrate surface. This electrolytic method offers many advantages including a simple application and two forms of surface protection: adding a physical barrier and alloying with the metal substrate to make it less galvanic, thus more resistant to corrosion. A more detailed technical explanation of the reaction mechanism and its relation to nature follows.

REACTION MECHANISM

The original concept behind the project was to extend the mineralization technology beyond a "passive" coating delivery system to an "active" controllable surface mineralization system. Previous work in the passive systems had shown that silicates delivered through an oil-based gel could chemically bond with a metal surface to form a metal silicate layer. Utilizing an environment set up with relatively higher amounts of silicate to that of molecular oxygen results in the metal silicate formation dominating. The passive process was diffusion-limited in two aspects. First the silicate was required to diffuse through the organic carrier. The second limiting factor was the diffusion of the metal and/or silicate through the newly formed metal silicate layer. A 200-angstrom thick mineral layer could take from hours to days to form. The process is represented in Figure 1.

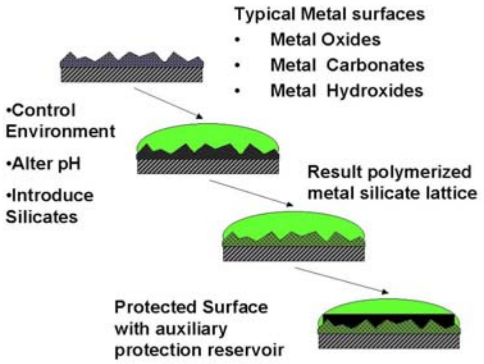


FIGURE 1. Typical Surface Conversion Chemical Process

HEALTH AND ENVIRONMENTALCONCERNS

The selection of adequate fasteners is often a critical problem for machinery maintenance and design. While a grade 8 ferrous bolt has high strength, it will rust. Replacing it with stainless can result in less strength, and it is subject to stress corrosion cracking. Often the best solution is to select a high strength ferrous bolt and then to select an effective coating for protection against corrosion. The coatings that are often selected are hexavalent chrome or cadmium plate, and often both. Hexavalent chrome and cadmium are both hazardous to health and the environment, and are being subjected to increasing regulation. In fact, the European Union End-of-Life Vehicle (ELV) directive requires elimination of lead, mercury, cadmium, and hexavalent chrome in any automobiles imported into or manufactured in the European Union after July 1, 2007. American automobile manufacturers are gearing up to be compliant with the EU directive. Both the Ford Motor Company and General Motors Corporation have issued performance specifications for cadmium and chromium free coatings. The ESM coating has met these specifications and is now being procured by both companies.

The Department of Defense is working on a joint project with NASA to find effective replacements for cadmium plating. Additionally, on August 27, 2004, the Acting Under Secretary of Defense for Acquisition, Technology and Logistics, Mr. Michael Wynne (2004), issued a memorandum that established the DoD Green Procurement Program (GPP). Green Procurement is the purchase of environmentally preferable products and services in accordance with Federally mandated "green" procurement preference programs identified in the concurrently published Green Procurement Strategy. As an effective alternative to cadmium and chromium coatings, ESM meets the GPP standard.

PERFORMANCE

GELS AND LUBRICANTS

Following successful laboratory, pier side and shipboard demonstrations of the effectiveness of the surface mineralization gel in preventing crevice corrosion in anchor chain detachable link cavities, the Navy in 1999 changed the Planned Maintenance System (PMS) to specify the use of the gel as the replacement for white lead and tallow in all surface ship anchor chain detachable links.

Also in 1999, following extensive testing such as is shown in Figure 2., the Navy issued MACHALT (Machinery Alteration) 526, which changed the design of the internals of weather deck watertight (WT) and airtight (AT) door dogging mechanisms to a new design. The basis of that design is the use of a mineralizing lubricant inside the spindle sleeve in the doorframe to stop the corrosion that had been the cause of dogging mechanism failure. In May 2002 a second MACHALT, 544, was approved to apply the same technology to ballistic type dogs in three WT doors in DDG-51 Class ships. The solution represented a significant saving for the fleet. The watertight door dogging mechanism corrosion problem was one of the top maintenance issues for the fleet.

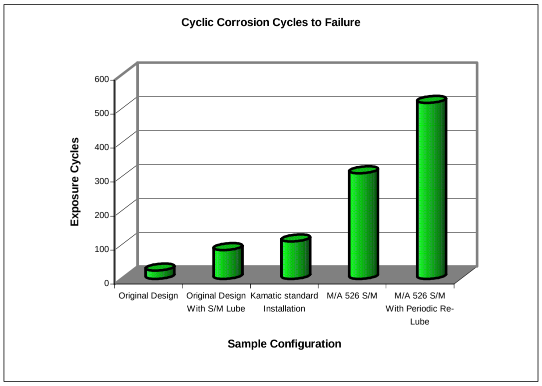


FIGURE 2. Report of Cyclic Corrosion Testing of Different Designs of Watertight Door Dogging Mechanisms

ELECTROLYTIC PROCESS

The electrolytic process provides an improved surface on articles by managing the surface chemistry and effecting a new surface through chemical reaction and interaction. The mineral-like surfaces are formed when mineral-forming precursors (silicates) are delivered to the surfaces of a metal or metal-coated article. The substrate contributes donor ions to react and/or interact with the delivered precursors, forming thin surface structures. These surfaces may exhibit highly desirable characteristics including corrosion resistance, temperature resistance, flexibility, coating adhesion, and chemical resistance.

TOP COATED PERFORMANCE

The mineral is extremely beneficial when employed as an inorganic mineral tie-coat for improving the bond between metal and organic topcoats. Improving adhesion with SM has a dramatic effect on the overall performance of the coating system, as exhibited in the following pictures in Figure 3.

FIGURE 3. ASTM B117 Salt Spray Performance of end-fitting fasteners at 3000 hours using coating systems on left: Zinc plate with SM topcoated with chromate-containing heat-cured epoxy, and on right: Zinc plate with yellow chromate topcoated with same chromate-containing heat-cured epoxy.

Figure 4 shows an even more dramatic result when using the electrolytic SM process with a topcoated heat cured epoxy with no chromate.

FIGURE 4. Brake Cable End Fittings zinc plated plus ESM and top coated with chromate free epoxy at 6552 hours ASTM B117 exposure.

Figure 5 shows the same electrolytic SM and topcoat used on bolts after 1000 hours in an ASTM B117 salt spray environment.

FIGURE 5. ASTM B117 Salt Spray Performance of Grade 8 bolts treated with ESM and top coated with chromate-free epoxy at 1000 hours.

The mineralized surface can be topcoated with a wide range of commercial coatings such as a silane, heat-cured epoxy, acrylics, alkyds, latex, or water-based coatings. Although the mineralization process is chromate-free, the chromate-free status of the entire coating system will be dependent upon the content of the topcoat. In other words, the ESM process can reduce chromate usage when topcoated with a chromate containing coating, or eliminate chromates altogether when used without a topcoat or when topcoated with a chromate free coating.

The development team has been working on a program to examine the feasibility of using this product as an alternative for cadmium plating. Figure 6 shows the test set up for the ongoing testing of ESM applications using the ASTM B117 protocol. This test involved continuous exposure to a salt fog rather than the cyclic exposure as in the Ford and GM protocols.

FIGURE 6. Test setup for ASTM B117 protocol.

Recognizing the different opinions on the various exposure and cyclic test protocols, the development team has moved forward to get the ESM products tested under both the General Motors GM 9540P and the Ford Arizona Proving Ground (APG) protocols as well as the ASTM B117 salt fog protocol. Figure 7 shows the results of a test conducted for Ford Motor Company under the Ford APG protocol.

FIGURE 7. SM treated fasteners with an epoxy topcoat and no red rust at 60 cycles of Ford APG protocol testing.

SECONDARY FORMING TOLERANCE

The ESM surface has also been shown to be tolerant of secondary forming of fasteners, such as rivets as shown in Figures 9 and 10. This is explained by the significant adhesion improvement observed, the amorphous nature of the metal silicate, and by the chemical bonding of the mineralized surface to the substrate.

FIGURE 9. ASTM B117 Salt Spray Performance of “bucked” rivets at 1000 hours using coating systems with and without surface mineralization.

FIGURE 10. ASTM B117 Salt Spray 4000 Hour ASTM B117 Performance of the “bucked” rivets from Figure 9.

CADMIUM REPLACEMENT TESTING OF FASTENERS

The development team has pursued a GM-9540P test program for evaluating the performance of ESM versus cadmium-plated and chromate-containing fasteners. The test has been completed and a summary of the findings is reported here. Figure 11 shows the GM-9540P test chamber being used for the test.

FIGURE 11. Test set up for GM-9540P cyclic testing of SM treated fasteners.

The team selected cadmium Type I (as plated), cadmium Type II (as plated plus hexavalent chromate treatment), and two hexavalent chromate treated fasteners as the ones against which to test. The cadmium-plated fasteners were prepared in accordance with the latest military and commercial specification for cadmium plating, SAE AMS-QQ-P-416A.

The team selected a variety of ESM treated fasteners to test against the cadmium plated and hexavalent chromate treated fasteners. They include zinc plated with ESM treatment, zinc plated with ESM treatment plus epoxy topcoat, and zinc-nickel alloy plated with ESM treatment.

Testing included properties in addition to the observations of corrosion in the test chamber. In addition to the corrosion condition observation the following factors were evaluated:

Torque tension physical parameters
Break loose torque after cyclic corrosion
Coating Thickness

The following mineral-based coating systems were tested:

Product E 0200 – zinc plate with electrolytic mineral process – Group 21
Product E 0300 – zinc plate with electroless mineral process – Group 22
Product E 0251 – E 0200 topcoated with high performance, chromate-free epoxy – Group 2
Product E 0351 – E 0300 topcoated with high performance, chromate-free epoxy – Group 5
Product E 0271 – E 0200 topcoated with clear, chromate-free coating with torque tension modifiers – Group 6
Product E 0272 – E 0200 topcoated with clear, chromate-free coating with advanced torque tension modifiers – Group 7
Product E 7200C – Clear ZnNi alloy plating with EMC process – Group 23
Product E 7200B – Black ZnNi alloy plating with EMC process – Group 24

In addition, these coatings were compared to other groups being tested:

CAD Type I – cadmium plate (Group 8)
CAD Type II – cadmium plate with hexavalent chromate conversion coating (Group 9)
Armor Coat – cadmium plate with epoxy topcoat (Group 10) Later found to be cadmium free
Product G – chromate-free coating system applied direct to steel (Group 11)
Product GX – chromate-free coating system applied direct to steel (Group 12)
Product MT– electroplated zinc + trivalent chromate + topcoated with heat-cured no-chrome epoxy topcoat (Group 15)
Product M - chromate-free coating system applied direct to phosphated steel (Group 17)
Zinc electroplate YELLOW *with yellow hexavalent chromate conversion coating* (Group 18)
Zinc electroplate OD *with olive drab hexavalent chromate conversion coating* (Group 19)

CYCLIC CORROSION TESTING

GM 9540P cyclic protocol was used to evaluate corrosion performance as it more closely represents corrosion performance than salt fog. Also the GM 9540P test is gaining in acceptance by military personnel as more representative of a field service environment, and the preferred method for accelerated corrosion testing. The GM 9540P protocol uses a 24-hour cycle to simulate a severe corrosion environment and includes a salt-water spray cycle, a hot dry period, and a high humidity period. According to the protocol, control coupons are to be tested alongside the samples to insure a predictable corrosion rate. The weight loss of coupons has been measured for this experiment and the results are shown in Figure 12. The trend line for actual coupon weight loss is slightly more severe than recommended in the published guideline, but overall within GM9540P protocol limits.

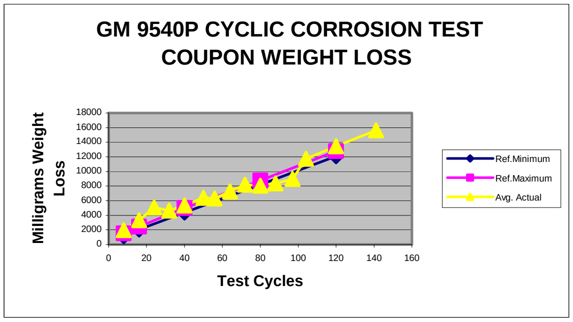


FIGURE 12. Coupon Weight Loss Cyclic Corrosion Results

With each coating system a total of 12 samples (1/2” X 13 X 2” Grade 8 bolts) were coated and mated with 6 free running ½” X 13 nuts and 6 prevailing torque ½” X 13 nuts. The bolts were assembled into ½” 5058 armor grade aluminum plate and placed in a GM 9540P corrosion chamber. Each coating system was inspected and photographed at 20 cycle intervals, and visual observations were recorded every 5 cycles. All coating systems were tested to 120 cycles, with several high performance coating systems continued to 180 cycles. Observations were made for white corrosion (on coating systems that contain zinc), base metal corrosion (as evidenced by red rust) and failure (as defined by ASTM as 5% red rust on significant surfaces. The observation data for each coating group is included in the Final Summary Report by Heimann and Soucie (2003).

OBSERVATION AT 120 AND 180 CYCLES

Upon completion of 120 cycles, the test protocol was extended to 180 cycles. Additional corrosion cycles were added to gain additional information to differentiate the high performance subset (including both Cadmium Type I and II). Several groups were removed from further comparison, with the remainder of the groups left in place until 180 cycles. The groups removed included:

Zinc Control – Group 20 – Average 5% failure on heads at 30 cycles.
Zinc Yellow Chromate – Group 18 – Average 5% failure on heads at 69 cycles
Zinc OD Chromate – Group 19 – Average 5% failure on heads at 46 cycles
Product E 0300 (uncoated control) – Group 22 –Average 5% failure on heads at 56 cycles
Product E 0200 (uncoated control) – Group 21 – Average 5% failure on heads at 39 cycles
Product E 0262 – Group 3 – Average 5% failure on heads at 115 cycles
Product E 0271 – Group 6 – Average 5% failure on heads at 110 cycles
Product E 0272 – Group 7 – Average 5% failure on heads at 90 cycles

Additionally, Group 10 was removed from the testing because it was determined that the coating specification for the product had been changed to be cadmium-free and therefore did not represent a cadmium control. The Group 13 fastener also was removed due to the catastrophic failure observed in breakaway evaluation.

Figure 13 shows the 180 cycle observations on head of the fasteners for high performance, non-chromate containing coating systems.

Group ID	**180 cycle observations (on heads**		
	# Samples white	# Samples red/failed	Rank
E 0251	All (Ave=39 cycles)	All free RED (Ave free nuts=131 cycles) 4 lock red	6th
E 0351	All (Ave = 54 cycles)	All (Ave = 112 cycles)	8th
E 7200C	5	NONE	2nd
E 7200B	3	NONE	1st
CAD Type I	2	9	5th
CAD Type II	1	2	3rd
G	*NA*	7	4th
M	*NA*	All (Ave free nuts=131 cycles)	7th

FIGURE 13. 180 CYYCLE OBSERVATIONS ON HEADS

Based on these observations of the bolt head, and using the # parts failed, #parts red, # parts white as the determining factor, the ranking of chromate free, high performance coatings at 180 cycles is shown in Figure 14.

Overall Rank at 180 Cycles
Product E 7200B
Product E 7200 C
CAD Type II
Product G
CAD Type I
Product E 0251
Product M
Product E 0351

FIGURE 14. Overall Rank at 180 Cycles

Photographs of each of the best performing coating systems at 180 cycles are proved in Appendix A.

TORQUE TENSION FACTORS – COEFFIENT OF FRICTION

Torque tension characteristics were evaluated using methods detailed in SAE 174M using Hahn & Kolb model 205s200Nm. The rotation used was 180deg/sec with a peak torque of 180 Nm. Torque tension data is obtained by recording torque and related tension at 5 tension points nominal and at 10 Kn intervals up to 50 Kn with exceptions at 30 Kn (actual was 28.3 Kn) and 40 Kn (actual was 41.1 Kn). Test bolts from groups 1-8, 11-21, 23, and 24 were evaluated. The bearing washers were square Wilson Garner hardened and zinc plated. Washer used once per side. Nuts used were plain Wilson Garner with dimensions of ½" X13.

The general trend for all coating systems indicates a linear relationship between torque and resulting tension as would be preferred of most fastener coating systems.

Torque Tension data were collected to isolate the raw data required for calculation of coefficient of friction. Coefficient calculations derived from DIN 946. The calculated coefficient of friction is shown on a bar graph (Figure 15) and is specific to the geometry and size of the fastener combinations tested. Preferred values may vary by industry and geographic region, but typical automotive specifications require a coefficient of friction between 0.14 and 0.18 to facilitate consistent robotic assembly to a desired clamp load. It is not unusual to add torque tension coatings to modify the surface tension of a coating system to be within range.

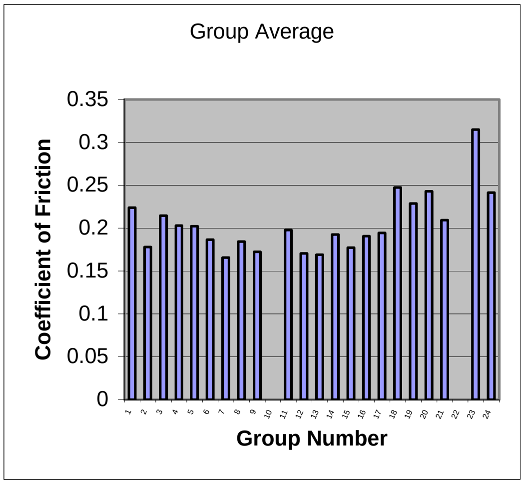


FIGURE 15. Coefficient of Friction by Group Number (average)

The parameter of k-factor for the tested groups ranged from 0.166 to 0.315. It is typical for the torque tension properties of coating systems to be targeted with commercially available torque tension modifier treatment.

BREAK LOOSE TORQUE AFTER CORROSION

Fasteners were installed into 5058 military armor grade aluminum plate to a torque value of 90-ft. lbs. Breakaway torque was measured on half the fasteners at every 20-cycle interval. Three replicates of both free running and prevailing torque nut assemblies were tested for breakaway torque at each sampling period. The remaining three free running and prevailing torque nut assemblies were tested for breakaway torque at the end of test at 120 cycles. For those groups that were left in corrosion testing, the sample sets were retorqued to 90-ft. lbs. and an additional breakaway was conducted at 180 cycles.

Test sample group 12 experienced structural failures during break away testing after 80 cycles of corrosion exposure. Inspection of the failed samples indicates that the basic bolt failure was tensile overload in nature. In addition it was observed that the heads of the bolts had actually imbedded in the aluminum plate. This condition supports the conclusion that the bolt failure was tensile in nature. Review of torque tension and coefficient of friction data indicates that the friction characteristics of Group 12 were not significantly different than other coatings when tested using zinc plated washers and plain steel bolts. Based upon this data it would be reasonable to use the same torque standard for sample preparation in cyclic testing.

Based upon the observations from this testing, it is theorized that the failures are the result of a lower net coefficient of friction when a Product GX bolt is used in conjunction with a Product GX nut. This condition may require that the installation torque specifications be adjusted when this combination is used. An additional concern remains, based upon the low friction characteristics of the type of fastener joint, that the exposure to vibration and temperature environmental factors could result in loss of joint clamp force over time and separation of the nut from the bolt.

Break away torque data are illustrated in Appendix B. The breakaway values follow a predicable trend of higher values for breakaway of prevailing torque nuts. Groups 23 and 24, Product E 7200B and Product E 7200C respectively, have results that are most similar to the cadmium benchmarks in Groups 8 and 9, Cadmium Type I and Cadmium Type II respectively.

THICKNESS

Thickness was measured for all samples using a Fischer MMS Permascope equipped with Beta Backscatter and Eddy Current inspection probes to measure plating thickness and organic coating thickness, respectively. Three samples were selected at random from each sample group for coating/plating thickness evaluation. A separate typical test specimen was stripped of plating for use as a zero baseline reference. The eddy current probe was zeroed to this sample. The Beta backscatter probe was calibrated using plastic reference films over a typical plated sample. Six measurements were made of each sample from each group with the eddy current probe and the Beta backscatter probe. All measurements were made on the flats of the hex head of the test bolt. This was the same area of the test article that was used for baseline and calibration. Average data for each 18-measurement block is shown in Figure 16.

	Plating Thickness (Eddy Current Probe)	Organic Coating (Beta Backscatter Probe)	Total Coating Thickness (Plating + Organic – as applicable)
Group No.	Mean (inch)	Mean (inch)	Mean (inch)
1	0.00045	0.00047	0.00092
2	0.00036	0.00026	0.00062
3	0.00035	0.00029	0.00064
4	0.00118	0.00059	0.00178
5	0.00128	0.00041	0.00169
6	0.00044	0.00003	0.00047
7	0.00046	0.00005	0.00051
8	0.00051	None	0.00051
9	0.00046	None	0.00046
10	Deleted from testing (no cadmium)		
11	None	0.00016	0.00016
12	None	0.00035	0.00035
13	None	0.00013	0.00013
14	None	0.00021	0.00021
15	0.00065	0.00013	0.00078
16	None	0.00062	0.00062
17	None	0.00062	0.00062
18	0.00121	None	0.00121
19	0.00111	None	0.00111
20	0.00110	None	0.00110
21	0.00044	None	0.00044
22	Deleted from testing		
23	0.00020	None	0.00020
24	0.00020	None	0.00020

FIGURE 16. Thickness Measurements

The data indicated a wide range of coating thickness in the tested groups. All coated samples were specified to have a coating thickness of less than 0.0004 in. However, several organic coating systems exceeded the anticipated limit as specified by the coating manufacturer. Several of the plating systems had a specified thickness on head of 0.0003-0.0004 in. However, several plated groups had much higher zinc plate thickness. The thinnest systems tested were Product E 7200C and Product E 7200B. The 7200 series coatings are between 0.00018-0.00022 inches.

Thickness was measured for all samples using a Fischer MMS Permascope equipped with Beta Backscatter and Eddy Current inspection probes to measure plating thickness and organic coating thickness, respectively. Three samples were selected at random from each sample group.

ADDITIONAL DATA ON DEZINCIFICATION

Supplemental information was obtained on the zinc nickel-plated fasteners to determine the magnitude of dezincification that might have occurred during cyclic corrosion testing. The initial nickel content of the zinc nickel coating is specified by the plater to be 13-15%, and is routinely analyzed under process control testing. Elemental analysis was conducted using X-Ray Fluorescence after 180 cycles of GM 9540P testing. Several random samples were selected from both Groups 23 and 24 and analyzed. The nickel content on 180 cycle samples ranged from 13.5-14.1 well within the range of concentration specified on initial samples, indicating that dezincification did not occur on the ESM processed samples under the conditions of the test.

CONCLUSION

This paper reviews several characteristics of fasteners and coating systems. In order to evaluate the coating systems and rank their relative performance, the following order of priority was given to the characteristics tested, and each was compared to the benchmark set with cadmium plated systems:

Corrosion Performance
Thickness
Breakaway Torque
Coefficient of Friction

The top performers based on this priority were Product E 7200C and Product E 7200B, Groups 23 and 24. These groups were found to exhibit the top corrosion performance at extremely long duration, and outperformed Cadmium I and II at 180 cycles. The extremely thin characteristic of this coating makes it a very good choice for cadmium replacement. The torque required to breakaway remained constant throughout the study. While the measured coefficient of friction of Groups 23 and 24 was not within automotive specifications, subsequent data show that post-ESM treatment may be used to achieve a k factor of 0.13 ± 0.03 to meet assembly standards. In addition, supplemental information for Groups 23 and 24 indicate that the dezincification failure mode of some zinc nickel coating systems did not occur for samples processed with ESM. It is believed that the ESM process serves to "seal" the zinc nickel with an electrochemical insulating layer, not allowing any zinc corrosion activity to occur by passivating the zinc phase to a zinc silicate layer, and thus eliminating the electrochemical drivers for dezincification.

Combination of zinc nickel with ESM should be further evaluated for wider application as a practical alternative to cadmium plating and hexavalent chromate. This combination coating system has also received multiple approvals from automotive OEM's and is being specified for use on various fasteners, hinges, and brackets among other parts.

REFERENCES

Heimann, Nancy, "A Cathodically Deposited Mineral Coating for Replacement of Cr (VI) and Cr. (III) Treatments of Zinc*," The American Electroplaters and Surface Finishers Society, Inc. Conference, February, 2001*

Heimann, Nancy and Soucie, Wayne, "Cyclic Corrosion Comparison of Plated and Topcoating Systems for Fastener Applications, Final Summary Report," Elisha Technologies Co., L.L.C. November 17, 2003

Koch, Gerhardus, H., Ph.D., Brongers, Michael P. H., Thompson, Neil G., Ph.D. Virmani, Y. Paul, Ph.D., Payer, Joe H., PhD., "Corrosion Costs and Preventive Strategies in the United States," *Report FHWA-RD-01-156, Federal Highway Administration, September 30, 2001*

The General Accounting Office (GAO), "Defense Management. Opportunities to Reduce Corrosion Costs and Increase Readiness," *GAO Report to the Congressional Committees GAO-03-753, July 2003.*

Wynne, Michael W., Acting Under Secretary of Defense for Acquisitions, Technology, and Logistics Memorandum of August 27, 2004, "Establishment of the DOD Green Procurement Program (GPP)."

CONTACT

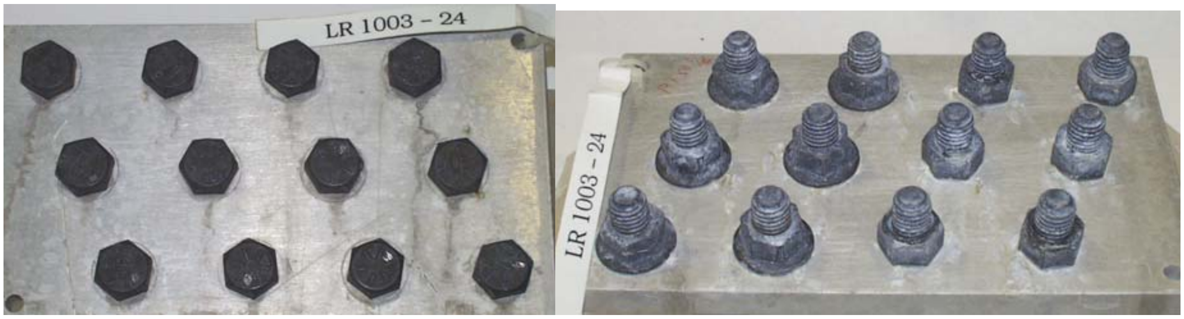
Ms. Nancy Heimann is Business Manager for Elisha Technologies. Ms. Heimann is responsible for Elisha interface with partners, and transfer of the Elisha technology to licensees. Elisha Technologies developed the surface mineralization technology and holds several patents in that field.

Captain George T. Simpson is a retired Engineering Duty Officer whose last active duty assignments were Director of Industrial Resources and Director of Hull Systems and Deck Machinery in the office of the Commander, Naval Sea System Command.

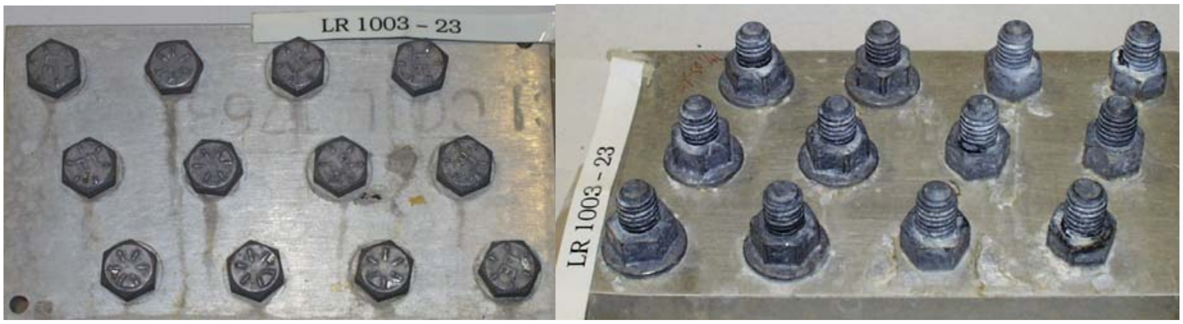
Elisha Technologies, L.L.C., is a member of the Orscheln group of companies. Orscheln, L.L.C., is a first-tier supplier and a major supplier of brake assemblies and components.

APPENDIX A – PHOTOGRAPHIC RESULTS

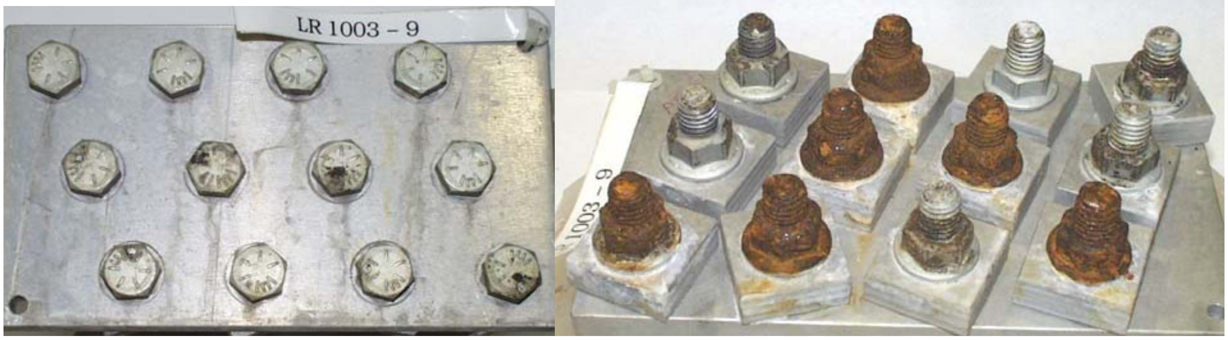
180 Cycles GM 9540P Protocol



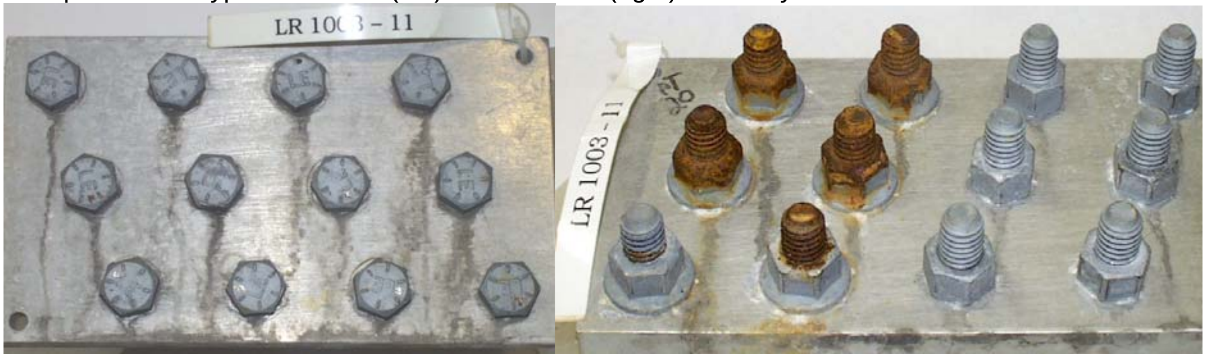
Group 24 – Product E 7200B – Heads (left) and Threads (right) at 180 cycles



Group 23 – Product E 7200C – Heads (left) and Threads (right) at 180 cycles



Group 9 – CAD Type II – Heads (left) and Threads (right) at 180 cycles



Group 11 – Product G – Heads (left) and Threads (right) at 180 cycles

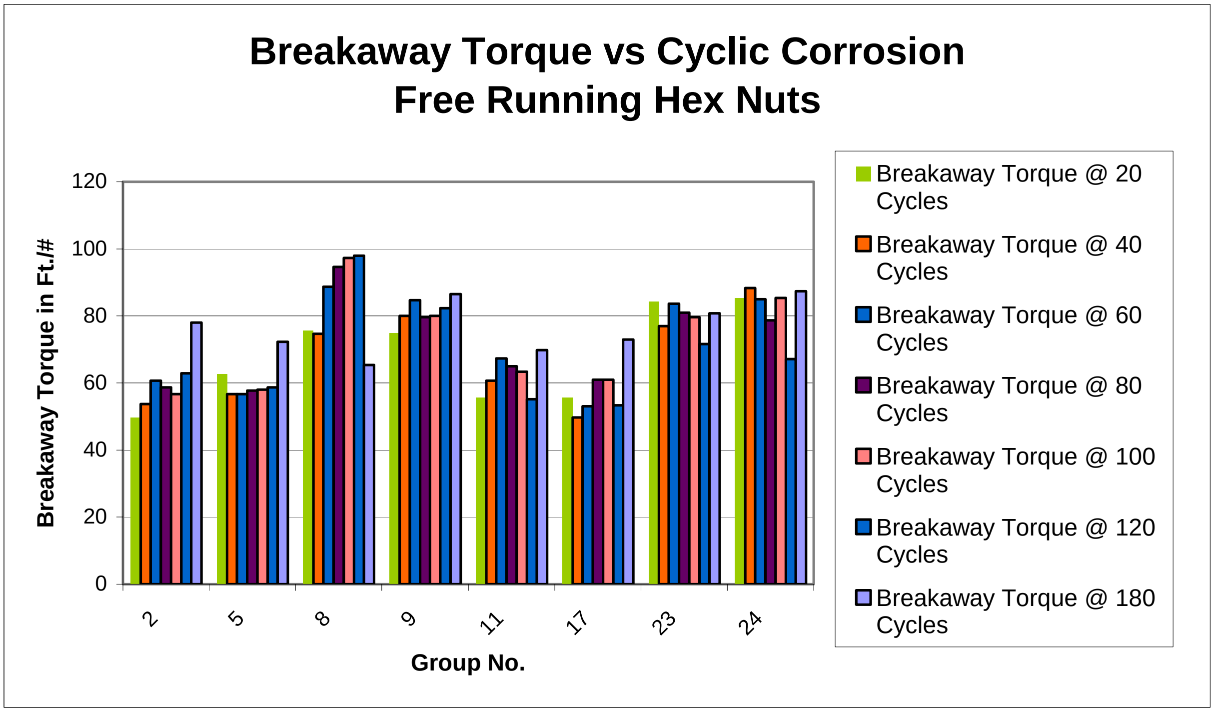
Group 8 – CAD I – Heads (left) and Threads (right) at 180 cycles

Group 2 – Product E 0251 – Heads (left) and Threads (right) at 180 cycles

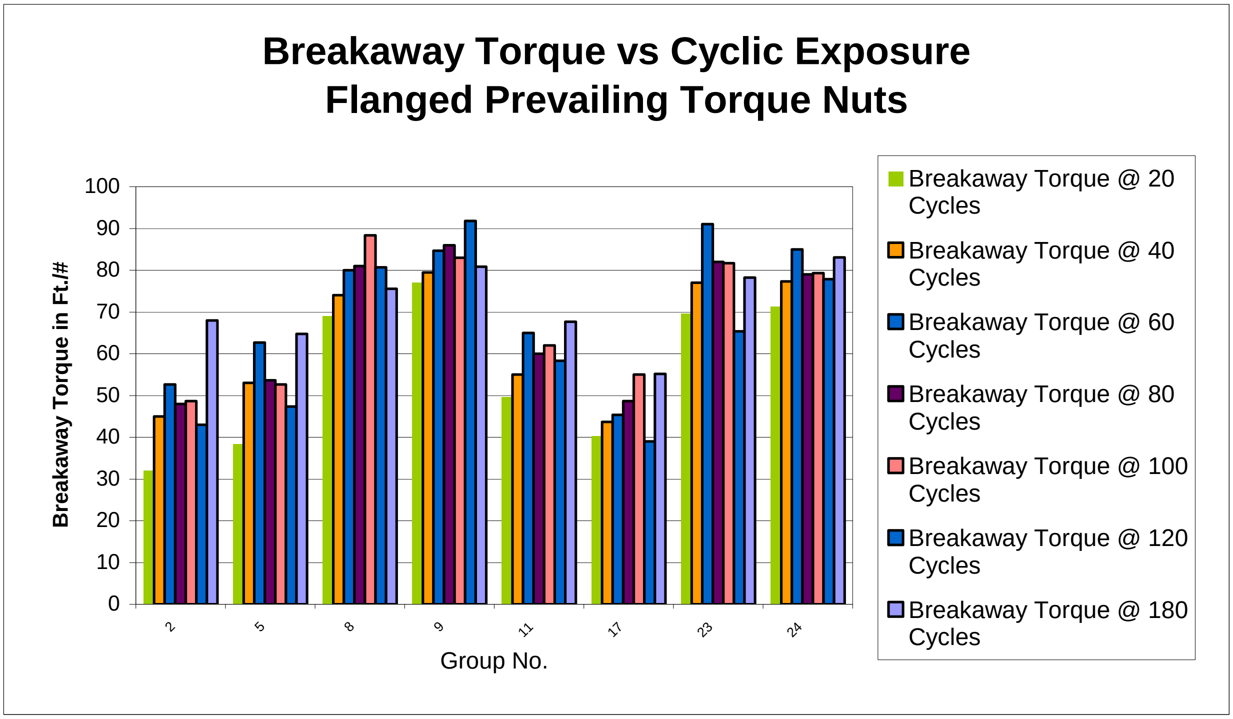
Group 17 – Product M – Heads (left) and Threads (right) at 180 cycles

Group 5 – Product E 0351 – Heads (left) and Threads (right) at 180 cycles

APPENDIX B – BREAK AWAY TORQUE VALUES



Break away Torque for Free Running Nuts for Selected Groups at Sample Cycles



Break away Torque for Prevailing Torque Nuts for Selected Groups at Sample Cycles