

# Environmentally Friendly Fastener Finishes

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**Research has revealed a material that functions as a direct replacement for cadmium, performing well in terms of galvanic and cosmetic corrosion rating, clamp load retention and ability to retain conductivity. Also, this material reduces cost of hardware by up to 40% compared with aluminum.**



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“The Perfect Finish” is something that the industry has been seeking for years. It is an elusive concept for which millions of dollars have been spent in developing, testing and qualifying possible alternative finishes, but most of these efforts are futile. In order for engineers to be most effective, a realization must be made that each finish, from phosphate to cadmium, has strengths and weaknesses that must be weighed in considering each application. It is with these considerations that progress can be made toward using the materials that have the closest resemblance to the qualities of cadmium and, in turn, accepting their weaknesses.

This paper describes a research study conducted on eight finishes that are potential replacements for cadmium. Information is specific to fasteners with regards to clamp load and corrosion, both cosmetic and galvanic. The scope was broadened to understand many different elements of each finish to give engineers information that is vital to recommending their usage as cadmium substitutes and exposing weaknesses of each finish. One inorganic alternative was found to be a drop-in replacement for cadmium, and another two were found to closely resemble performance of cadmium in all respects except for electrical conductivity.

## BACKGROUND

Cadmium plating has been the finish of choice for many engineers for a number of years. It offers many qualities such as excellent corrosion resistance, consistent torque-tension, bimetallic compatibility and thickness within

standard thread tolerances. It is still used in many applications that cannot sacrifice any of the qualities that cadmium offers.

Initially, automotive OEM's established a deadline to remove cadmium by 1995. **DaimlerChrysler Corporation** enacted testing programs to fill the hole in their fastener finish requirements<sup>1</sup>. Chrysler conducted a Design of Experiment (DOE) to qualify alternatives that met strict performance requirements and also adhered to **OSHA** and **EPA** regulations. This DOE resulted in the selection of the **DACROMET 320® L Coating System** because it closely resembled cadmium in fastener applications. As a result, Chrysler was compliant with the OSHA and EPA regulations prior to the established deadline. **Metal Coatings International Inc. (MCII)** was involved with this DOE and has done continuous research and quality control testing of its products and therefore had the experience in testing to assist the U.S. Army in a research study to qualify alternatives.

The extreme use of their equipment in critical situations caused the military to continue to use cadmium for many applications. The delay in switching from cadmium plated hardware proved beneficial due to the large amount of information compiled by automotive OEM's. The military was able to sort through the data produced by automotive qualifications and select the coatings that performed well in the predetermined areas, which in-turn resulted in a substantial cost savings.

Three years ago the Army embarked on a cadmium replacement journey, testing numer-

ous finishes as potential candidates.<sup>2</sup> Although there was still no “perfect finish” found, this testing resulted in the qualification of a solvent-based coating that closely resembled cadmium with regards to corrosion protection, bi-metallic compatibility and clampload retention. The weaknesses exposed were lack of conductivity, high coating thickness and the dependence on a supplemental lubricant to meet Army torque charts. Another attribute that must be considered is that this coating is solvent based and therefore high in Volatile Organic Compounds (VOC). Due to the VOC content, application facilities require expensive air treatment equipment to reduce pollution that otherwise would escape into the environment surrounding the facilities.

### TEST FORMAT

Despite the popularity of its coating systems, Metal Coatings was not included in the initial testing. Following completion, MCII was able to work with the Army to duplicate the test. The information accumulated in this study will give test data that is essential to military engineers to ensure integrity of fastened joints. It will also allow the Army to standardize on one or two finishes to be used and maximize economies of scale for cost savings.

Due to the versatility of cadmium, the study contained many different tests concentrating on those advantages. The most imperative applications for cadmium are fasteners and as a result the part selected for testing was a ½-13 Grade 8 bolt. The military currently uses both Free Running and Prevailing Torque nuts in various applications, so both nuts were used in the testing. The Free Running hex and hex flange nuts were Grade 8. The Prevailing Torque hex nuts (all metal type) were Grade C; the Prevailing Torque flange nuts (all metal type) were Grade G. The hex nuts were used for torque-tension testing, whereas the hex flange nuts were used for corrosion testing.

The Aluminum used was AA 5083, which was selected to duplicate military armor. The bars were cut and machined to the dimensions 18 x 2.5 x 1.38 inches. Each bar had twelve holes machined into it: six to be used for Free Run-

ning nuts, and the other six to be used for Prevailing Torque nuts. The bolt hole diameter was 0.525 +/- 0.002 inch, and a Chromate conversion coating per MIL-C-5541 was applied prior to fastener installation to provide a visual basis from which to determine pitting corrosion following testing. The bars were machined with a 15° angle on the ends, so the bars would be aligned properly in the accelerated corrosion chamber when installed on 2x4 boards.

### THE TESTS CONDUCTED

**Torque-Tension.** There have been many documented occurrences of fasteners being loosened or missing from vehicles which ultimately resulted in damage to property or injury to persons involved. Joint integrity is a vital concern when assembling vehicles, especially those being used by the armed forces. Each fastened joint has dynamics of its own and critical joints need to be installed to the proper clamp load in order to hold an assembly together. This clamp load is obtained by applying torque to a fastener to utilize its tensile strength. Most assembly operations control the clamp load in a joint by designating a torque range to be followed when installing the fasteners. Friction is the main obstacle in obtaining proper clamp load. Different finishes vary in their degree of lubricity, so whereas one finish may not reach clamp load within a certain torque range, other finishes, with a very low K-factor, may cause the bolt to meet clamp load, stretch or even break. Low and consistent torque-tension characteristics are essential to obtain proper clamp load in every fastener that is installed.

As the initial study indicated, generic torque charts are inadequate to compensate for the numerous finishes and lubricants that are used. As a result of this inadequacy, questions arose about the quality of fastened joints. A benefit of conducting this testing is that the military torque charts can be used as the acceptance criteria and in order for a finish to be qualified it must meet the predetermined characteristics. As these qualities are met, standard assembly procedures can remain constant while the finish and corresponding performance change.

The testing took place in MCII's **A2LA/ISO 9001** accredited torque-tension lab using an **RS Technologies Labmaster 9504**. Test format was per SAE J174 for the Free Running Torque applications and IFI 100/107 for the Prevailing Torque applications. Using a load cell, this unit is capable of measuring clamp load in a joint at different specified torques. From this data, one is able to determine if a finish has the lubricity to ensure a quality joint. In order to register consistency, twelve bolts of each finish were tested, and the mean data was used to determine the final rating. From datapoints received from this testing, K-factor (nut-factor), standard deviation, average clamp load and torque range at 90 ft-lbs. can be determined. The plus/minus three-sigma data spread was used to give a statistical confidence that the clamp load would be achieved reproducibly.

**Corrosion Protection.** The validity of the Salt Spray Test (per ASTM B117) as an indica-



Labmaster 9504 used for torque-tension testing



Fasteners installed in aluminum bars are mounted in Singleton CCT chamber for corrosion testing to GM 9540P

tor of real world performance has long been questioned. Many assert that it is effective if used as a quality control tool, but it does not have a high correlation to real-life performance.

Parts that are put into service are rarely kept in a wet, high salt, controlled-temperature environment, but rather parts are exposed to environments that include salt mist, humidity, dry and hot conditions. An accelerated corrosion test that has a high correlation to real-life exposure is **General Motors GM 9540P**, which includes the previously mentioned, more realistic cycles. General Motors uses the duration of 80 cycles to equate to 10 years in service, but due to the high cost and long life expectancy of military vehicles, the test duration was expanded to 120 cycles. Previous testing determined that the corrosion rates were different in different areas of accelerated corrosion chambers, therefore the assemblies were rotated clockwise every 20 cycles to equalize the severity of testing.

To add greater severity, but one that duplicates field applications, the fasteners were installed into Aluminum bars to introduce a dissimilar metal. When metals that are notably separate in the galvanic series are mated together, corrosion of the less noble metal will be accelerated due to the galvanic reaction. Flange nuts were selected for this portion in order to increase the surface area of the evaluated surface. A hardened steel washer of the same finish (or cadmium if the same finish was not available) was used under the head of the bolt to protect against embedding of the head into the Aluminum. The reason the same finish was used was to eliminate any bimetallic corrosion that may have occurred with other finishes.

The bolts were assembled/disassembled using a calibrated dial-torque wrench and were installed to 90 ft-lbs. The same individual installed all the bolts and once they were installed they were checked a second time to ensure that the 90 ft-lbs. was maintained. The installation torque of 90 ft-lbs. was chosen for three main reasons:

- To duplicate typical applications for installing Aluminum armor to military vehicles.
- To test the amount of clampload retention (or relaxation) that may occur during exposure due to corrosion or lubricity of the fastener.
- To test the susceptibility to Hydrogen Embrittlement.

While it is not a foolproof indicator, a cost effective means to test for Hydrogen Embrittlement is to subject the finished part to normal installation stresses. It is only when a fastener is put in stress that failure as a result of Hydrogen Embrittlement will occur. This applies to both Internal Hydrogen Embrittlement (IHE), caused as a result of the finishing process, in addition to External Hydrogen Embrittlement (EHE), caused by the chemical reaction occurring during corrosion. In both of these failure methods, hydrogen diffuses into the steel microcrystals and separates the once-fused steel particles.

In order to quantify the amount of corrosion that occurred as a result of the bimetallic cell, the Aluminum bars were measured for total pitted volume ( $\text{mm}^3$ ) and maximum pit depth (mm). The pitted volume was measured with the aid of a binocular-scope and various measuring devices. The pit depth was measured using a **Leco** microhardness tester with a calibrated height adjustment. In both of these cases the area surrounding each hole was measured and the average of these values was used for ranking. The same individual using the same guidelines as the initial study conducted pitting corrosion testing at **United Defense**.

**Conductivity.** Essential for grounding applications, conductivity is required in order to protect the expensive electronics utilized in military vehicles. In many cases, expensive specialty finishes are required in order to retain the conductivity essential to protect the vehicle. Cadmium displays excellent conductivity characteristics, which are retained throughout testing. Following installation of the fasteners to the aluminum bars, an Ohmmeter was used to test the conductivity. One probe was placed on the aluminum and the other was placed on two or more nuts of the finish being tested. Readings greater than 20,000 Ohms were considered infinite resistance and the finish was deemed non-conductive. The initial readings were used as the baseline to see how the finish reacts to the corrosion testing.

**Thickness.** Utilization of standard thread sizes is an important element in qualifying an

alternative to cadmium. If a special fastener is required, it drives up the costs associated with the vehicles, and broadens the tax dollars that are required to pay for it. Initial installation is one consideration, but when the vehicle needs to be serviced, finding the special-order replacement hardware will be especially difficult.

The thickness testing was conducted on a Fischerscope using magnetic induction. This testing requires an unfinished bolt to be used for a baseline and a flat surface (hex head or flat of a nut) on which to take a measurement. A total of three readings were taken on each part (bolt, PT hex, PT flange, FR hex and FR flange) using an average of the readings as a total thickness.

**Cost Analysis.** Just as the military engineering standards are acclimated to the performance of cadmium, the same is true for the purchasing system. The finish that provides the most consistent functional benefits would be eliminated if it were not cost-effective in replacing cadmium. A cost factor was included to



Fischerscope instrument used for thickness testing

provide engineering and purchasing a definitive test from which to gather essential information. The cost factor used cadmium as a baseline (cadmium=1) and was obtained using major sources of supply in the Detroit, MI metropolitan area.

**Finishes Tested.** This study included eleven finishes including some lubricants to assist in assembling the Prevailing Torque nuts. As previously mentioned, cadmium + yellow dichromate and cadmium + wax (per Federal specification, QQ-P416, Class 2, Type 2) were used as the upper baseline for corrosion, and zinc + yellow dichromate (per ASTM B633, Class Fe/Zn 8, Type 2) was used as the lower baseline.

Different variations of inorganic water-based coatings were the focus of this test study, due to their large demand worldwide in applications similar to those targeted for replacement.

The DACROMET® and GEOMET® Coating Systems are water based Zn/Al coatings with varying degrees of lubricity. The DACROMET® Coating Systems (applied per Ford S301, DaimlerChrysler PS 5873L and PS 9666) contain chrome and have been used in automotive and military applications as cadmium replacements. There are differences in the DACROMET® Coating Systems tested, and those differences are that DACROMET 500® contains an integral lubricant in the basecoat, DACROMET 320® L utilizes the PLUS® L lubricated sealer, and DACROMET 320® XL uses the PLUS® XL lubricated sealer. The GEOMET® Coating Systems (applied per DaimlerChrysler PS 5873L, PS 9666 and GMW 14) share a chrome free base coat, which is the leading development in the finishing industry to eliminate chrome in vehicles. GEOMET® L and GEOMET® XL utilize the same chrome free PLUS® L and PLUS® XL sealers to provide lubricity and additional corrosion protection. Coatings 6 and 7 are solvent-based organic coatings, which contain Hexavalent chrome (6) and are Hexavalent chrome free (7). Finally Tin Zinc, currently being used for applications requiring moderate corrosion protection and

conductivity, was tested. All finishes were applied in industrial, bulk finishing operations to obtain real-world performance.

## TEST RESULTS

**Torque-Tension.** The information obtained from the torque tension testing included the torque range, average clamp load and K-factor at 90 ft-lbs. This information is essential in planning fastened joints because there must be statistical confidence out of numerous bolts that the proper clamp load is achieved and retained. In the initial study, some of the finishes tested required supplemental lubricants to achieve the desired K-factor of 0.13-0.15, but in the “dry” state, these finishes reacted similar to the previous study. **Table 1** shows the results of the torque-tension testing.

**Corrosion Protection Results.** Following exposure to 120 cycles of GM 9540P, the assemblies were rinsed in warm water, allowed to dry and then rated according to cosmetic corrosion, break-loose torque and galvanic corrosion. According to the GM 9540P test method, bare steel coupons were tested to provide a benchmark with regards to severity. The corrosion of these coupons was 63% higher than the test parameters, indicating the parts were exposed to an extremely severe environment.

**Cosmetic rating.** All of the finishes were compared to each other regarding the amount of red/white corrosion on the nut and threads of

Table 1.

Torque-Tension								
(Completed before testing on separate parts)								
Finish	K-Factor		Avg. Clampload (lbs.)		Load Range- PT (lbs.)		Load Range- FR (lbs.)	
	PT	FR	PT	FR	High	Low	High	Low
DACROMET 500® B	0.190	<b>0.174</b>	11,384	<b>12,404</b>	13,527	9,240	<b>14,023</b>	<b>10,785</b>
Cadmium + Yellow	Not Tested	<b>0.214</b>		<b>10,074</b>			<b>11,937</b>	<b>8,211</b>
Cadmium + Wax	0.131	<b>0.116</b>	16,483	<b>18,701</b>	19,844	13,123	<b>22,554</b>	<b>14,848</b>
DACROMET 320® L	0.132	<b>0.131</b>	16,328	<b>16,442</b>	18,015	14,641	<b>18,204</b>	<b>14,680</b>
GEOMET® L	0.120	<b>0.124</b>	17,999	<b>17,445</b>	19,449	16,549	<b>18,505</b>	<b>16,385</b>
Coating 6	0.157	<b>0.156</b>	13,720	<b>13,882</b>	15,412	12,028	<b>15,559</b>	<b>12,205</b>
DACROMET 320® XL	0.087	<b>0.095</b>	20,875*	<b>18,989*</b>	22,850	18,656	<b>20,539</b>	<b>17,440</b>
GEOMET® XL	0.086	<b>0.096</b>	20,875*	<b>18,718*</b>	21,919	19,831	<b>19,368</b>	<b>18,068</b>
Zinc + Yellow	Not Tested	<b>0.175</b>	Not Tested	<b>12,355</b>	Not Tested	Not Tested	<b>15,347</b>	<b>9,363</b>
Tin Zinc	Not Tested	<b>Not Tested</b>	Not Tested	<b>Not Tested</b>	Not Tested	Not Tested	<b>Not Tested</b>	<b>Not Tested</b>
Coating 7	Not Tested	<b>Not Tested</b>	Not Tested	<b>Not Tested</b>	Not Tested	Not Tested	<b>Not Tested</b>	<b>Not Tested</b>

\* @ 75 ft-lbs.

PT= Prevailing Torque

FR= Free Running

the bolt. The best and worst finishes remained constant throughout the testing, but the finishes in the middle changed positions. **Table 2** shows the cosmetic corrosion rating of the different finishes.

**Break-Loose Torque.** Following cosmetic rating, the bolts were disassembled and



Prevailing Torque nuts coated with DACROMET 500® B at 120 cycles GM 9540P



Prevailing Torque nuts coated with DACROMET 320® L at 120 cycles GM 9540P



Prevailing Torque nuts coated with GEOMET® L at 120 cycles GM 9540P



Prevailing Torque nuts coated with Cadmium + Yellow at 120 cycles GM 9540P

the break-loose torque was recorded. The target break-loose torque was 90 ft-lbs., which indicates clampload retention throughout the test, although variations were expected due to the severity of the exposure. Due to white or red corrosion on the Tin Zinc parts, the break-loose torque was higher than expected. **Table 3** shows the results of the break-loose torque testing.

GM 9540P- 120 Cycles Cosmetic Corrosion Rating	
1	DACROMET 500® B
	Cadmium + Yellow
	Cadmium + Wax
2	DACROMET 320® L
3	GEOMET® L
4	Coating 7
5	Coating 6
6	Tin Zinc
7	DACROMET 320® XL
8	GEOMET® XL
9	Zinc + Yellow

**Galvanic rating.** Following removal of the fasteners, the aluminum bars were sent to United Defense for pitting corrosion evaluation.

Break Loose Torque (ft-lbs.)				
Finish	80 Cycles		120 Cycles	
	PT	FR	PT	FR
DACROMET 500® B	73.5	68.8	82.3	92.2
Zinc + Yellow	126.7	226	91.7	81
Tin Zinc	Not Tested		126.7	96.7
Cadmium + Wax	117.7	107.2	95	106.3
Cadmium + Yellow	139.5	78.3	95	81.6
DACROMET 320® L	62.8	65.5	72.4	76.6
GEOMET® L	59.2	68.7	76.3	72.6
Coating 7	Not Tested		64.2	66.2
Coating 6	52.5	54.8	64.2	64.5
DACROMET 320® XL	40.8	40.7	48	50.2
GEOMET® XL	33.7	30.7	51.3	49.5

PT= Prevailing Torque FR= Free Running

The intent for the pitted volume measurement was to include only the surface area of the pits and not the non-corroded areas between the pits. The pit depth was measured using the microscopic method, by focusing on the top of the sample and refocusing on the bottom of the pit while measuring the vertical height change. With regards to relative performance, the results were consistent with the previous study. **Table 4** describes the results of the galvanic rating.

**Conductivity Results.** Following exposure, the assemblies were tested to explore the effects of the corrosion testing on the conductivity of the finish. Four finishes were found to retain their conductivity throughout 120 cycles. Others exhibited acceptable conductivity at the beginning of the testing, but lost those attributes

Table 4.

GM 9540P- Galvanic Corrosion Rating 120 Cycles		
Finish	Pitted Volume (mm <sup>3</sup> )	Max. Pit Depth (mm)
DACROMET 320® L	0	0
DACROMET 500® B	0.002	0.02
GEOMET® L	0.320	0.10
Coating 6	0.448	0.14
Coating 7	2.300	0.20
Cadmium + Yellow	2.928	0.48
Tin Zinc	30.950	0.50
Zinc + Yellow	421.920	0.90
Cadmium + Wax	Not Measured	Not Measured
DACROMET 320® XL	Not Measured	Not Measured
GEOMET® XL	Not Measured	Not Measured

by completion. **Table 5** outlines the conductivity test results.

**Thickness Results.** Bolts of each finish were set aside in order to conduct thickness testing to ensure that the thickness was at least

Table 5.

Ohms Resistance			
Finish	Before Testing	80 Cycles	120 Cycles
Cadmium + Yellow	1	0.1	0.1
Cadmium + Wax	1	0.1	0.1
Tin Zinc	0.5	0.5	0.5
DACROMET 500® B	6	6	5
DACROMET 320® XL	10	10,000	Infinite
DACROMET 320® L	4	Infinite	Infinite
Zinc + Yellow	2	Infinite	Infinite
GEOMET® L	4	Infinite	Infinite
GEOMET® XL	10	Infinite	Infinite
Coating 7	20,000	Infinite	Infinite
Coating 6	Infinite	Infinite	Infinite

what the specified minimum, but not excessively more, which would result in problems mating a nut to a bolt. Although the thickness of the pitch and root of the threads can not be determined using this method, there is a direct correlation between the tested areas and the pitch/root thickness. **Table 6** describes the

Table 6.

Thickness (mils)			
Finish	Bolt	PT Nut	FR Nut
DACROMET 500® B	0.382	0.385	<b>0.380</b>
Cadmium + Yellow	0.490	0.441	<b>0.428</b>
Cadmium + Wax	0.441	0.423	<b>0.398</b>
DACROMET 320® L	0.383	0.340	<b>0.403</b>
GEOMET® L	0.528	0.478	<b>0.535</b>
Coating 7	0.770	1.200	<b>1.000</b>
Coating 6	0.765	0.746	<b>0.686</b>
Tin Zinc	Not Tested		
DACROMET 320® XL	0.441	0.382	<b>0.430</b>
GEOMET® XL	0.647	0.485	<b>0.540</b>
Zinc + Yellow	0.339	0.274	<b>0.286</b>

thicknesses associated with each of the finishes tested.

**Cost Analysis Results.** In order for testing to be beneficial, the qualified finishes must be readily available in the market at a cost-effective price. A cost factor was determined using cadmium as a baseline, so engineers would know the relative price increase/decrease compared with their current cadmium plated fastener purchase. **Table 7** shows the cost factor using the cost of cadmium as 1.

## CONCLUSIONS

The testing concluded that DACROMET 500® B could be used as a direct cadmium

Table 7.

Cost Factor	
Finish	Cost
DACROMET 320® L	0.5
DACROMET 500® B	0.6
GEOMET® L	0.6
DACROMET 320® XL	0.6
GEOMET® XL	0.6
Zinc + Yellow	0.6
Coating 7	0.7
Cadmium + Yellow	1.0
Cadmium + Wax	1.0
Coating 6	1.0
Tin Zinc	1.2

replacement for all engineering applications. This coating system performed well in all of the categories tested, offering excellent corrosion protection in a very thin film. The galvanic corrosion rating was superior to cadmium with the cosmetic corrosion rating equaling the performance of cadmium. The clampload retention was comparable to the cadmium baseline, however the torque characteristics were more lubricious. The lubricity was not sufficient to meet the specified criteria, so the addition of a dry film lubricant to the coated nuts is required. DACROMET 500® B also retained its conductivity (although it was slightly less than Tin Zinc) and reduces the cost of hardware by 40% compared to cadmium.

DACROMET 320® L and GEOMET® L performed better than cadmium with regards to galvanic corrosion, reducing the amount of pitted volume and maximum pit depth. The

cosmetic corrosion protection was somewhat inferior to cadmium, but the difference is negligible considering the severity of the test. The torque characteristics of these coating systems, which utilize the same topcoat, were within the acceptable range according to the Army torque charts with regards to both Prevailing Torque and Free Running applications. The weakness that was exposed through this testing is that the conductivity measured before exposure was not retained throughout the test duration. At 50% and 60% the cost of cadmium, respectively, these coatings can be deemed as cadmium replacements for some applications, but not as a drop-in replacement in all engineering areas.

Coatings 6 and 7 performed better than Zinc Plate + Yellow Chromate, however they do not offer superior corrosion resistance. Coating 7 showed worse galvanic corrosion ratings than the water based coatings with regards to both pit depth and pitted volume. Also, the torque characteristics of Coating 6 indicate that a supplemental lubricant is necessary to meet the torque characteristics specified by the Army. The same is expected from Coating 7 due to the close resemblance of the topcoat, but testing was not completed in this research study. Another weakness that was originally exposed in the previous study was that these coatings do not allow an electrical current to be passed through the substrate even at the beginning of testing.

Another concern for guaranteeing joint integrity is the reduction of the clamp load after exposure to testing. With a 28% reduction between the installation torque and break loose torque, careful attention must be paid in assembly. At twice the thickness of cadmium, functionality in mating a nut to a bolt could potentially be a problem with the expectation that the threads would have to be undersized in order to accommodate the thickness. At the same or slightly lower cost than cadmium, these coatings can be characterized as acceptable alternatives with regards to corrosion protection, but consideration must be made for the torque characteristics and the health hazards associated with their application facilities.

Tin Zinc provided mediocre performance in all areas except conductivity, in which it performed

second only to cadmium. White corrosion products were apparent very early in the testing, which lead to somewhat higher break loose torque values following testing. These corrosion products also showed that there was a galvanic reaction when mated with the aluminum, resulting in considerable pitting. At a cost 20% higher than cadmium, Tin Zinc is recommended for applications that require conductivity, but are not in an area that involves contact with aluminum, due to the bimetallic reaction.

DACROMET 320<sup>®</sup> XL and GEOMET<sup>®</sup> XL outperformed Zinc + Yellow Dichromate, but were rated near the bottom of the cosmetic corrosion ranking. The lubricity of each of these coating systems, which share the same sealer, is too low, and when measurements were attempted at the standard 90 ft-lbs. bolts were broken. The parameters were changed slightly to 75 ft-lbs. in order to obtain valuable data from the testing. The thickness of these coatings was comparable to cadmium; however they did not perform well with regards to break loose torque or conductivity. At 60% the cost of cadmium, these coatings may be chosen selectively for applications requiring a low K-factor to ease the installation of large fasteners.

The results of this study show inherent benefits and weaknesses of the finishes tested. The DACROMET 500<sup>®</sup> B was the only finish that performed equivalent to or better than cadmium in all applications. The other benefits it offers is that it is VOC compliant and is cheaper than cadmium. With results and properties similar to DACROMET 500<sup>®</sup> B, DACROMET 320<sup>®</sup> L and GEOMET<sup>®</sup> L are viable options for many applications as a cost-effective environmentally compliant alternative to cadmium. The other finishes tested have weaknesses just as many previously tested options do, but still can not be accepted as drop-in replacements.

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Prevailing Torque and Free Running nuts coated with  
DACROMET 500® B at 120 Cycles GM 9540P

## Cadmium Replacement Matrix

		DACROMET 500® B		DACROMET 320® L		GEOMET® L		Cadmium / Yellow Dichromate	
Finish									
Specification		Ford S301		Ford S301 DC PS 5873L		GMW 14 DC PS 5873L		QQ-P-416	
Nut Type		PT	FR	PT	FR	PT	FR	PT	FR
Finish Thickness- Nut		0.385	<b>0.380</b>	0.340	<b>0.403</b>	0.478	<b>0.535</b>	0.441	<b>0.428</b>
Bolt		0.382		0.383		0.528		0.490	
GM 9540P Results									
80 Cycles	Total Cor.	1		4		8		2	
120 Cycles	Total Cor.	1		2		3		1	
Galvanic Cor. Rating									
Avg. Pitted Area (mm)		0.1		0.0		3.2		6.1	
Avg. Pit Depth (mm)		0.02		0.00		0.10		0.48	
Salt Spray Rating									
500 hours		1		3		2		1	
1000 hours		1		2		3		1	
First Red Rust		-----		936		936		-----	
Break Loose Torque									
80 Cycles		73.5	<b>68.8</b>	62.8	<b>65.5</b>	59.2	<b>68.7</b>	139.5	<b>78.3</b>
120 Cycles		82.3	<b>92.2</b>	72.4	<b>76.6</b>	76.3	<b>72.6</b>	95	<b>81.6</b>
Avg. Clampload @ 90 ft-lbs.		11,384	<b>12,404</b>	16,328	<b>16,442</b>	17,999	<b>17,445</b>	Not Tested	<b>10,074</b>
Torque		13,527	<b>14,023</b>	18,015	<b>18,204</b>	19,449	<b>18,505</b>	Not	<b>11,937</b>
Range		9,240	<b>10,785</b>	14,641	<b>14,680</b>	16,549	<b>16,385</b>	Tested	<b>8,211</b>
K-Factor @ 90 ft-lbs.		0.190	<b>0.174</b>	0.132	<b>0.131</b>	.120	<b>0.124</b>	Not Tested	<b>0.214</b>
Ohms Resistance									
Before / 80 / 120 cyc.		6 / 6 / 5		4 / Inf. / Inf.		4 / Inf. / Inf.		1 / 0.1 / 0.1	
Cost		0.6		0.5		0.6		1	

## Cadmium Replacement Matrix

Finish	Cadmium / Leached Dichromate / Wax**		Tin Zinc		Coating 6		Coating 7			
Specification	QQ-P-416				S426		GM 3359			
Nut Type	PT	FR	PT	FR	PT	FR	PT	FR		
Finish Thickness	0.423	<b>0.398</b>			0.746	<b>0.686</b>	1.2	<b>1</b>		
Nut/Bolt	0.441		Not Tested		0.765		0.77			
GM 9540P Results										
80 Cycles	Total Cor.		3		6		7		5	
120 Cycles	Total Cor.		1		6		5		4	
Galvanic Cor. Rating										
Avg. Pitted Area (mm)		Not Measured		61.9		3.2		11.5		
Avg. Pit Depth (mm)		Not Measured		0.50		0.14		0.20		
Salt Spray Rating										
500 Hours		1				4				
1000 Hours		1		Not Tested		5		Not Tested		
First Red Rust		-----				648				
Break Loose Torque										
80 Cycles	117.7	<b>107.2</b>	Not Tested		52.5	<b>54.8</b>	Not Tested			
120 Cycles	95	<b>106.3</b>	126.7	<b>96.7</b>	64.2	<b>64.5</b>	64.2	<b>66.2</b>		
Avg. Clampload @ 90 ft-lbs.		16,483	<b>18,701</b>	Not Tested		13,720	<b>13,882</b>	Not Tested		
Torque		19,844	22,554	Not Tested		15,412	15,559	Not Tested		
Range		<b>13,123</b>	<b>14,848</b>	Not Tested		<b>12,028</b>	<b>12,205</b>	Not Tested		
K-Factor @ 90 ft-lbs.		0.131	<b>0.116</b>	Not Tested		0.157	<b>0.156</b>	Not Tested		
Ohms Resistance										
Before / 80 / 120 cyc.		1 / 0.1 / 0.1		0.5 / 0.5 / 0.5		Inf. / Inf. / Inf.		20,000 / Inf. / Inf.		
Cost		1.0		1.2		1.0		0.7		

\*\*Wax is Joncote