Evaluation of Alloy Coatings Being Developed As Alternatives to Cadmium Coatings

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ABSTRACT

Electroplated cadmium coatings are used on military aircraft parts to provide corrosion resistance, low contact resistance, and/or lubricity. Unfortunately, cadmium is a hazardous (toxic) material and environmental regulations and Executive Orders call for a reduction in its use and eventual elimination. Several electroplated alloys and multi-layer coatings have been investigated as alternatives to cadmium for a variety of substrate materials. This paper focuses on several commercial or near commercial zinc alloy and zinc-containing coatings that may provide a satisfactory alternative that meets the three performance criteria listed above. Emphasis is placed on coatings that will not cause hydrogen embrittlement of high-strength steel substrates. The results of thickness, adhesion, corrosion resistance, and hydrogen embrittlement screening tests are presented and compared to cadmium as a control and ion vapor deposited aluminum, one of the other possible alternatives, as a benchmark.

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BACKGROUND AND OBJECTIVE

Cadmium coatings have been applied to many Department of Defense (DoD) weapon systems used on land, on sea, and in the air for many years because of their desirable properties [1]. In particular, cadmium provides excellent sacrificial corrosion protection to steels, lubricity on threaded components, low contact resistance on electrical connectors, and it protects against galvanic corrosion when dissimilar metals are in contact with each other (such as aluminum alloys and steels). Electroplated cadmium coatings are especially useful because they may be applied to a wide range of substrate materials with a variety of GEOMETries, including blind holes, internal diameters, threads and other complex features. This latter attribute is referred to as a "non-line-of-sight" capability. Some coating methods, such as physical vapor deposition and thermal spray, can only apply coatings to surfaces placed directly in front of the application tool, which limits their usefulness. These are referred to as "line-of-sight" coating methods.

Unfortunately, cadmium is classified as a toxic chemical and a possible human carcinogen and it is deposited from a bath that contains cyanide salts, which are categorized as toxic and reactive [1-4]. Also, if the coatings are to be painted, a chromate post-treatment is required for maximum paint adhesion and corrosion resistance. Consequently, worker health and safety and the environment must be protected in a number of ways. Emissions from the plating bath are regulated by the Occupational Safety and Health Administration, Clean Air Act, and the Environmental Protection Agency. Wastewaters are regulated by the Clean Water Act, and the plating sludge is regulated by the Resource Conservation and Recovery Act. Other federal, state, and local legislation and mandates also constrain the use of electroplated cadmium coatings. It is no surprise, then, that the elimination of cadmium plating in the defense industrial base would reduce environmental, safety and health risks and reduce legal liability associated with facilities being in compliance. In addition, there would be some cost avoidance if a satisfactory alternative coating were used. In the United States, savings would accrue from the avoidance of the need for workers to wear personal protective equipment, decreased monitoring and reporting, and reduced waste treatment costs. For fielded weapon systems, there also would be the avoidance of having to handle cadmium plated parts and the associated waste streams during maintenance, repair, and overhaul operations. This applies both to operations in the United States and worldwide.

DoD, therefore, has an active program to identify, evaluate, validate, qualify, and transition alternatives to electroplated cadmium coatings in its fielded weapon systems and support equipment, as well as providing alternatives for weapon systems and support equipment in the planning and design stages.

CANDIDATE ALTERNATIVE COATINGS

Alternatives under investigation by the Air Force include physical vapor deposited aluminum, electrodeposited aluminum, electroplated tin-zinc, zinc-nickel, and aluminum-manganese alloys, metal-filled polymers, and metal-filled ceramic (cermet) coatings [5-7]. Applications being considered include landing gear, electrical connectors, structural components, springs, fasteners, and other discrete metal parts. Table 1 provides a matrix of some alternatives and their possible applicability. Note that some of the pretreatments (such as cleaning and acid dips) and electrodeposition of alloys (if acid plating baths are used) have the potential to cause hydrogen embrittlement, especially with high strength steel substrates. Performing a hydrogen relief bake after coating deposition often can mitigate this embrittlement on high strength steels.

Table 1. Alternatives and Their Possible Applicability

Coating	High Strength Steel Parts (>200ksi)	Low Strength Steel Parts (<200ksi)	Fasteners	Electrical Connectors
PVD Aluminum*	✔	✔	✔	✔
Electroplated Aluminum**	✔	✔	✔	✔
Electroplated Al-Mn Alloy***	✔	✔	✔	✔
Electroplated Sn-Zn, Zn-Ni Alloys	(✔)	✔	✔	✔
Cermets****	✔	✔		
Metal-filled Polymers*****		✔	✔	

* Commercially known as Ion Vapor Deposited (IVD) aluminum.
** Commercial example is AlumiPlate, which is deposited from an organic electrolyte bath.
*** Navy development, deposited from a molten salt bath.
*** Commercial example is SermeTel W, which contains aluminum.
**** Commercial example is DACROMET, which contains aluminum and zinc.

In this paper the focus is on the screening and evaluation of the zinc-containing alloys and polymer coatings.

Coatings Selected and Specimen Preparation

As part of larger studies [5-7] the following coatings were selected for testing as possible candidates to replace electroplated cadmium coatings.

Table 2. Zinc-containing Alternatives Selected for Evaluation

Coating	Vendor/Supplier
Cadmium Control	A, B
IVD Aluminum Benchmark	C/D
DACROMET® 320L*	E
DACROMET® 500B*	E
GEOMET® L*	E
Tin-zinc (1-20%)**	Naval Air Depot (NADEP), Cherry Point/F
Acid Zinc-nickel (7-12%)**	C/G
Alkaline Zinc-nickel (12-15%)**	H
Zinc-nickel-phosphorous**	J
Zinc-nickel-silicon dioxide**	J

* Dip, spin coated and cured.
** Electrodeposited coatings.

Vendors deposited their coatings on 4130 steel panels measuring 4 by 6 inches for most tests and on 4340 steel bars for the hydrogen embrittlement testing. About one half of the electroplated panels and bars received a vendor recommended post-treatment to provide what they considered to be their best coating. The remainder of the electroplated panels and bars received a trivalent chromium post-treatment (TCP) that has been developed by Navy personnel at NAVAIR, Patuxent River, MD. Some of the coating vendors/suppliers recommended that a post-treatment (e.g., conversion coating) not be applied to their products. This is indicated in the various tables that summarize the results obtained.

Property data for cadmium coatings (QQ-P-416F, Class 2, Type II) were used as a baseline for comparing the candidates[1]. In addition, because IVD aluminum (Class 3, Type II) has been accepted by the DoD as an alternative to cadmium for some applications, comparisons with its properties also were made. The cadmium control and aluminum benchmark coatings were applied by several vendors/suppliers, as indicated in Table 2.

Test Protocols

To date, the Air Force has developed two Test Protocols for evaluating cadmium alternatives. One is for low strength steel components, and one is for high strength steel components. Specific test protocols for fasteners and electrical connectors may be completed in the future. Because of the different performance requirements in service, each Test Protocol contains a

[1] The equivalent ASTM Standard Specification for Electrodeposited Coatings of Cadmium is B 766-86 (re-approved 1998).

different suite of tests that has been accepted by the Air Force facilities that apply cadmium coatings. As a result, data from these tests can provide the information necessary for the Air Force to make a decision about implementing an alternative coating technology.

For the evaluation reported here, the tests listed in Table 3, and described in References 5, 6 and 7 were performed by Concurrent Technologies Corporation (*CTC*); the National Defense Center for Environmental Excellence (NDCEE, operated by *CTC*); or the other laboratories indicated. Not all tests were performed on all test samples (panels or bars).

Table 3. Testing Matrix for Cadmium Alternatives

Test	Reference	Testing Facility
Appearance (visual quality)	QQ-P-416F	*CTC*, Johnstown, PA
Thickness (cross-section measurement)	ASTM B 487	*CTC*, Johnstown, PA
Adhesion (bend test)	ASTM B 571 QQ-P-416F, Section 4.6.2	*CTC*, Johnstown, PA
Corrosion Resistance* - Unscribed Salt Fog	ASTM B 117-94	*CTC*, Johnstown, PA
Corrosion Resistance* - Scribed Salt Fog	ASTM B 117-94	*CTC*, Johnstown, PA
Corrosion Resistance** - Scribed SO_2/Salt Fog	ASTM D 1654-92	Touchstone Research Laboratory, Triadelphia, WV
Corrosion Resistance*** - Cyclic, Scribed and Unscribed	GM 9540P/B Accelerated Corrosion Test	NDCEE, Johnstown, PA
Hydrogen Embrittlement****	ASTM F 519-93	Dirats Laboratory, Westfield, MA; Omega Research

* 96 hours exposure, inspection every 24 hours.
** 500 hours exposure, SO_2 introduced every3 hours.
*** 120 cycles, 24-hours each cycle.
**** 200 hours sustained tensile load test.

Test Results

Appearance: All coatings had acceptable visual appearance in accordance with the Federal Standard QQ-P-416F.

Thickness: The specification for cadmium coatings calls for a thickness in the range of 0.0003 to 0.0005 inch (0.3 to 0.5 mil). This thickness was chosen for the alternatives evaluated in this investigation. The thickness of IVD aluminum - as typically deposited - should be in the range of 0.5 to 0.99 mil according to the MIL-DTL-83488 specification.

The deposited average thickness of each of the coatings evaluated is listed in Table 4. With the exception of the Zn-Ni-P and Zn-Ni-SiO_2 electroplated alloy coatings, most thicknesses were within, or just outside the range allowed by the specifications for Class 2 coatings. According to the vendors/suppliers, process optimization and better process control should enable the thickness requirements to be met in a production setting.

Table 4. Thickness Measurement Results for Alternatives with Different Post-Treatments

Coating	Thickness, mil Vendor Post-Treatment	Thickness, mil NAVAIR TCP
Cadmium Control	**0.29-0.40**	**0.44**
IVD Aluminum Benchmark	**0.49-1.0**	0.45
DACROMET 320L*	0.25	N/A**
DACROMET 500B*	**0.38**	N/A**
GEOMET L*	0.25	N/A**
Tin-zinc	**0.37**	TBD
Acid Zinc-nickel	**0.41-0.61**	0.78
Alkaline Zinc-nickel	**0.39**	TBD
Zinc-nickel-phosphorous	0.74***	0.81
Zinc-nickel-silicon dioxide	0.90*	0.91

* No post-treatments. *** However, vendor states that this coating has a SiO_2 post-treatment.
** N/A = not applicable; TBD = testing yet to be done.

Adhesion: Results from the bend test are summarized in Table 5 below. The acid and alkaline Zn-Ni coatings and the Sn-Zn coatings passed. The three metal-filled organic coatings failed, but two only exhibited very minor flaking. Similarly, the two ternary alloy coatings failed the bend test, but the Zn-Ni-SiO_2 coating only exhibited some minor cracking and flaking.

Table 5. Coating Adhesion Test Results for Alternatives with Different Post-Treatments

Coating	Adhesion Result	Adhesion Result
	Vendor Post-Treatment	**NAVAIR TCP**
Cadmium Control	**Pass**	TBD**
IVD Aluminum Benchmark	**Pass**	TBD
DACROMET 320L*	Fail (major flaking)	N/A
DACROMET 500B*	Fail (minor flaking)	N/A
GEOMET L*	Fail (minor cracking/flaking)	N/A
Tin-zinc	**Pass (no flaking)**	TBD
Acid Zinc-nickel	**Pass (no flaking)**	N/A
Alkaline Zinc-nickel	**Pass (no flaking)**	N/A
Zinc-nickel-phosphorous	Fail (some flaking)	Fail (very minor flaking)
Zinc-nickel-silicon dioxide*	Fail (minor cracking/flaking)	Fail (very minor flaking)

* No post-treatments.
** N/A = not applicable; TBD = testing yet to be done.

Corrosion Resistance – Unscribed and Scribed Salt Fog: Results from the ASTM B 117 salt fog test with unscribed coatings are presented in Table 6 (with vendor applied post-treatments) and Table 7 (with the NAVAIR TCP post-treatment). The ratings shown are based on the ASTM D 1654 scale, where 10 is equivalent to no corrosion or failure visible, 9 is equivalent to 0 to 1 % of the area corroded or failed, and 0 is equivalent to over 75 % corrosion or failure visible. A rating of 9-10 was considered acceptable, and a rating of 7-8 was considered to be a marginal failure. In contrast, ratings below 7 were considered to be failures when summarizing the all the results by a color code in Table 13.

For the alternatives with a vendor applied post treatment (Table 6) all the scribed panels, except the IVD control, showed good corrosion resistance. For those alternatives without a vendor recommended post-treatment, all of the scribed panels passed, although away from the scribe marks the DACROMET 500B and GEOMET L metal-filled organic coatings exhibited some corrosion attack. In contrast, on the unscribed panels, only the cadmium control and aluminum benchmark, DACROMET 320L, and acid Zn-Ni coatings passed the test criterion. It should be pointed out that the coatings that failed did not receive a vendor recommended post-treatment.

For the panels that received the NAVAIR TCP treatment, all the scribed panels tested (acid Zn-Ni, Zn-Ni-P, Zn-Ni-SiO_2 coatings) passed the criterion, but the unscribed panels failed. In contrast, the scribed and unscribed cadmium coatings failed this test, as did the unscribed aluminum coating benchmark. The latter exhibited mixed results for the scribed panels in this test. The scribed area failed the criterion but the unscribed areas on these panels passed.

Table 6. Salt Fog Corrosion Testing Results for Alternatives with Vendor Post-Treatments

Coating	Vendor Post-Treatment	Scribed Panels*		Unscribed Panels*	Corrosion Type**
		Scribed Area	Unscribed Area		
Cadmium Control	Yes	**10**	**9**	**9**	BCP
IVD Benchmark	Yes	5	**9**	**9**	BCP
DACROMET 320L*	No	**10**	**9**	**10**	BCP,WCP, W/YCP
DACROMET 500B*	No	**10**	4	3	W/YCP
GEOMET L*	No	**10**	7	7	B/WCP, WCP,
Acid Zinc-nickel	Yes	**10**	**9**	**10**	BCP, WCP, Pits
Zinc-nickel-phosphorous	No	**10**	**9**	6	BCP
Zinc-nickel-silicon dioxide	No	**10**	**9**	6	BCP, R, WCP, Blisters

* Corrosion rating per ASTM D 1654: 10 = no corrosion/failure; 0 = over 75 % corrosion/failure.
** CP = corrosion products: B = black; R = red (rust); W = white; Y = yellow.

Table 7. Salt Fog Corrosion Testing Results for Alternatives with TCP Post-Treatment

Coating	Scribed Panels*		Unscribed Panels*	Corrosion Type**
	Scribed Area	Unscribed Area		
Cadmium Control	7	0	0	WCP
IVD Aluminum Benchmark	5	**10**	**10**	N/A
Acid Zinc-nickel	**10**	**9**	2	BCP, B/WCP
Zinc-nickel-phosphorous	**10**	**9**	6	WCP, Cracking
Zinc-nickel-silicon dioxide	**10**	**9**	6	BCP

* Corrosion rating per ASTM D 1654: 10 = no corrosion/failure; 0 = over 75 % corrosion/failure.
** CP = corrosion products: B = black; R = red (rust); W = white.

Corrosion Resistance – Scribed SO_2/Salt Fog: Results from the ASTM G85-98 test are summarized below in Table 8 (with vendor post-treatments) and Table 9 (with NAVAIR TCP treatment). The same rating scale was used as that used for the standard Salt Fog test and the same color code was used in Table 13.

Table 8. SO_2/Salt Fog Testing Results for Alternatives with Vendor Post-Treatments

Coating	Vendor Post-Treatment	Rating after 160 hours		Rating after 500 hours	
		Scribed Area*	Unscribed Area*	Scribed Area*	Unscribed Area*
Cadmium Control	Yes	5	0	0	0
IVD Aluminum Benchmark	Yes	**10**	7	0	0
DACROMET 320L*	No	**9**	5	0	0
DACROMET 500B*	No	7	0	0	0
GEOMET L*	No	**10**	5	0	0
Acid Zinc-nickel	Yes	0	0	0	0
Zinc-nickel-phosphorous	No	6	0	0	0
Zinc-nickel-silicon dioxide	No	8	0	0	0

* Rating per ASTM D 1654: 10 = no corrosion/failure; 0 = over 75 % corrosion/failure.

Table 9. SO_2/Salt Fog Corrosion Testing Results for Alternatives with TCP Post-Treatment

Coating	Rating after 160 hours		Rating after 500 hours	
	Scribed Area*	Unscribed Area*	Scribed Area*	Unscribed Area*
Cadmium Control	1	0	0	0
IVD Aluminum Benchmark	**10**	7	0	0
Acid Zinc-nickel	0	0	0	0
Zinc-nickel-phosphorous	5	0	0	0
Zinc-nickel-silicon dioxide	8	0	0	0

* Rating per ASTM D 1654: 10 = no corrosion/failure; 0 = over 75 % corrosion/failure.

For those coatings that received no vendor recommended post-treatment or the vendor applied post-treatment, all failed this particular test with only a few exceptions. These were the IVD aluminum benchmark with a post-treatment and the DACROMET 320L and GEOMET L without a post-treatment in the scribed areas. However, even these coatings exhibited some corrosion attack in areas away from the scribe marks. For those coatings with the NAVAIR TCP treatment (Table 9), only the IVD aluminum benchmark passed, but even then only in the scribed area. The Zn-Ni-SiO_2 scribed coating exhibited marginal performance in the scribed areas.

Corrosion Resistance – GM Cyclic Test: The tin-zinc and alkaline zinc-nickel alloy coatings were subjected to this accelerated corrosion test rather than the standard Salt Fog or SO_2/Salt Fog tests. This test combines alternating periods of wet and dry exposure to simulate actual service conditions. The results are reported in Table 10. The ratings for the unscribed areas were based on the appearance of red rust, and do not reflect the first appearance of another type of corrosion product (e.g., “white rust”).

Table 10. Cyclic Corrosion Testing Results for Alternatives with Vendor Post-Treatments

Coating	Vendor Post-Treatment	Rating after 120 Cycles*	
		Scribed Area**	Unscribed Area*
Cadmium Control	None	6	**10**
Cadmium Control	Yes	**10**	**10**
IVD Aluminum Benchmark	None	3	4
IVD Aluminum Benchmark	Yes	8	**9**
Tin-zinc	None	0	0
Tin-zinc	Yes	0	0
Alkaline Zinc-nickel	None	4	6
Alkaline Zinc-nickel	Yes	**9**	**10**

* Rating per ASTM D 1654: 10 = no corrosion/failure; 0 = over 75 % corrosion/failure based on observation of red rust.
** Average creepage rating for scribes.

In the scribed areas, only the cadmium control and the alkaline Zn-Ni coatings with a vendor applied post-treatment passed this test, although the IVD aluminum benchmark exhibited marginal performance. In the unscribed areas, both controls and the alkaline Zn-Ni coating with the vendor applied post-treatments passed. The only untreated coating to pass was the cadmium control.

Hydrogen Embrittlement: Table 11 (with vendor post-treatments) and Table 12 (with NAVAIR TCP treatment) summarize all of the hydrogen embrittlement test results. When failure occurred, the hours at which it happened are listed.

All the coatings that received the vendor recommended post-treatment, or had no recommended post-treatment, met the 200 hours criterion with the exception of the Zn-Ni-P and Zn-Ni-SiO_2 coatings. The latter had received a post-treatment.

Table 11. Hydrogen Embrittlement Results for Alternatives with Vendor Post-Treatments

Coating	Vendor Post-Treatment	Post Heat Treatment*	Hours Exposed	Result
Cadmium Control	Yes	375 ^oF	**200**	**No failure**
IVD Aluminum Benchmark	Yes	None	**200**	**No failure**
DACROMET 320L*	No	610 ^oF	**200**	**No failure**
DACROMET 500B*	No	575 ^oF	**200**	**No failure**
GEOMET L*	No	600 ^oF	**200**	**No failure**
Acid Zinc-nickel	Yes	375 ^oF	**200**	**No failure**
Zinc-nickel-phosphorous	Yes	None	127	Failure
Zinc-nickel-silicon dioxide	Yes	None	73	Failure

Table 12. Hydrogen Embrittlement Results for Alternatives with TCP Post-Treatment

Coating	TCP Treatment	Post Heat Treatment*	Hours Exposed	Result
Cadmium Control	Yes	N/A	**200**	**No failure**
IVD Aluminum Benchmark	Yes	N/A	**200**	**No failure**
DACROMET 320L*	No	N/A	**200**	**No failure**
DACROMET 500B*	No	N/A	**200**	**No failure**
GEOMET L*	No	N/A	**200**	**No failure**
Acid Zinc-nickel	Yes	N/A	**200**	**No failure**
Zinc-nickel-phosphorous	Yes	N/A	**200**	**No failure**
Zinc-nickel-silicon dioxide	Yes	N/A	**200**	**No failure**

All the coatings that received the TCP treatment met the 200 hours criterion for passing the hydrogen embrittlement test.

SUMMARY AND DISCUSSION

The performance data obtained for the various alternative coatings applied by the various vendors and suppliers that participated in this study are summarized in Table 13 in the context of whether or not the requirements criteria - based on the baseline performance of electroplated cadmium coatings - were met. An IVD aluminum coating also was used as a benchmark for the alternative coatings.

The entries in the table are color-coded to assist in the interpretation of the results. Green represents an acceptable performance, yellow indicates a marginal failure (criterion almost met), and red correlates with a definite failure.

Table 13. Summary of Results for the Cadmium Alternatives Tested

Candidate Alternative Coating	Appearance	Thickness	Adhesion	Unscribed Salt Fog (96 hr)	Scribed Salt Fog (96 hr)	SO_2/Salt Fog (500 hr)	Hydrogen Embrittlement
Cd (LHE) Control with VPT*	Pass	Pass	Pass	Pass	Pass	Fail	Pass
Cd (LHE) Control with TCP*	Pass	Pass	Pass	Fail	Fail	Fail	Pass
Al (IVD) Control with VPT	Pass	Pass	Pass	Pass	Fail	Fail	Pass
Al (IVD) Control with TCP	Pass	Fail	Pass	Pass	Fail	Fail	Pass
DACROMET 320L**	Pass	Fail	Fail	Pass	Pass	Fail	Pass
DACROMET 500B**	Pass	Pass	Fail	Fail	Pass	Fail	Pass
GEOMET L**	Pass	Fail	Fail	Fail	Pass	Fail	Pass
Sn-Zn with VPT	Pass	Pass	Pass	Fail✣	Fail✣	N/A✣✣	Pass
Sn-Zn with TCP	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Acid Zn-Ni with VPT	Pass	Fail	Pass	Pass	Pass	Fail	Pass
Acid Zn-Ni with TCP	Pass	Fail	Pass	Fail	Pass	Fail	Pass
Alkaline Zn-Ni with VPT	Pass	Pass	Pass	Pass✣	Pass✣	Fail	Pass
Alkaline Zn-Ni with TCP	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Zn-Ni-P**	Pass	Fail	Fail	Fail	Pass	Fail	Fail
Zn-Ni-P with TCP	Pass	Fail	Fail	Fail	Pass	Fail	Pass
Zn-Ni-SiO_2**	Pass	Fail	Fail	Fail	Pass	Fail	Fail
Zn-Ni-SiO_2 with TCP	Pass	Fail	Fail	Fail	Pass	Fail	Pass

* VPT = Vendor recommended/applied post-treatment (may incorporate chromates); TCP = NAVAIR trivalent chromium post-treatment.
** No post-treatment specified or used by vendor.
✣ GM 9540P/B Cyclic Corrosion Test.
✣✣ N/A = not applicable or not tested.

Control and Benchmark Coatings

With respect to the cadmium control, even with a post-treatment this coating could not pass the SO_2/Salt Fog test 500-hour requirement. With the vendor recommended, hexavalent chromiumcontaining post-treatment this coating system passed the scribed and unscribed Salt Fog test criteria. The trivalent chromium (NAVAIR TCP) post-treatment did not provide as much protection in these tests, failing the 96-hour requirement.

The IVD aluminum benchmark coating performed almost as well as the cadmium coating control. As deposited thickness was more variable, but this is not considered to be a major drawback. Better control of the processing parameters should yield coatings with acceptable thickness. Although this benchmark coating passed the unscribed Salt Fog Test 96-hour requirement, it failed the scribed Salt Fog test. The type of post-treatment did not make a difference in these tests.

Metal-filled Polymer Coatings

The three coatings investigated that fell under this category did not receive a post-treatment before testing at the vendor/supplier's recommendation. Control of coating thickness was not satisfactory for two of the coatings. However, repetition of the dip/spin/cure cycle would enable thicker coatings to be obtained. All three variations of this coating type failed the adhesion test but passed the scribed Salt Fog test. In contrast, only the DACROMET 320L coating passed the unscribed Salt Fog test, although the GEOMET L coating was rated as a marginal failure. Like the control and benchmark coatings, the three coatings failed the SO_2/Salt Fog test. But, as expected, all three variations passed the hydrogen embrittlement test.

Overall, this type of coating did not perform as well as the control and benchmark coatings.

Electroplated Alloy Coatings

Tin-Zinc Alloys: The alloy coating investigated - with the vendor recommended conversion coating applied as a post-treatment - passed the appearance, thickness, adhesion, and hydrogen embrittlement tests but failed the scribed and unscribed Salt Fog tests. This alloy coating was not subjected to the SO_2/Salt Fog test. It was not evaluated with the trivalent chromium post treatment.

Binary Zinc-Nickel Alloys: Two types of Zn-Ni alloy coatings were investigated. One coating was deposited from a recently developed, slightly acidic plating bath, the other was deposited from a conventional alkaline plating bath. The latter was tested with a vendor/supplier applied post-treatment, but not with the trivalent chromium (NAVAIR TCP) post-treatment. The former was tested with both the trivalent chromium and the vendor/supplier recommended post-treatments. The alkaline Zn-Ni alloy coating performed as well as the cadmium control and better than the IVD aluminum benchmark coatings.

The acid Zn-Ni alloy coating with the vendor/supplier applied post-treatment also performed as well as the cadmium control and better than the IVD aluminum benchmark coatings, with the exception of thickness control. Because thickness is only indirectly related to performance, and could be made to conform to the requirement with better process controls, this was not considered to be a serious shortcoming. The acid Zn-Ni alloy coating with the trivalent chromium post-treatment exhibited similar performance, except that it did not pass the requirement for the unscribed Salt Fog test. As for all the other coatings, neither of this alloy coating type passed the SO_2/Salt Fog 500-hour requirement.

Ternary Zinc-Nickel Alloys: Two types of developmental, "ternary" Zn-Ni alloy coatings were investigated. One type contained phosphorous (Zn-Ni-P) and the other contained silicon dioxide particles (Zn-Ni-SiO_2). Both types were tested with the trivalent chromium and the vendor/supplier recommended post-treatments.

Table 13 shows that both types of coating performed in a similar manner. Appearance and scribed Salt Fog test results were satisfactory, as were the hydrogen embrittlement results for the coatings given a NAVAIR TCP treatment. In all other tests, these coatings exhibited failure or marginal failure. Overall, the coatings treated with the trivalent chromium post-treatment performed a little better than those with the vendor/supplier recommended post-treatments.

CONCLUSIONS

All coatings investigated passed the appearance/quality criteria.

For many coatings thickness deviations from the requirement were observed, but these can be rectified by implementing better process controls during deposition. The deviations seen were not considered to represent a serious shortcoming.

Adhesion, as measured by a bend test, varied for the alternative coatings studied. In general, the metal-filled polymer coatings and the ternary Zn-Ni-based coatings failed this test, while the binary Sn-Zn and Zn-Ni alloy coatings passed. The metal-filled polymer coatings do not form a metallurgical bond with the substrate material.

The majority of the coatings failed to meet the 96-hour requirement in the unscribed Salt Fog test. Porosity and other defects in the coatings may have caused this failure. However, an investigation of coating integrity and structure was beyond the scope of this investigation. The exceptions were one metal-filled polymer coating and some of the binary Zn-Ni alloy coatings. In contrast, most coatings passed the scribed Salt Fog test 96-hour requirement. The exception was the Sn-Zn alloy coating.

All coatings, including the control and benchmark coatings, failed the 500-hour requirement of the SO2/Salt Fog test. This test exposes the coatings to a much more aggressive environment.

Most coatings passed the hydrogen embrittlement test with the exception of some of the ternary Zn-Ni-based coatings.

For the cadmium control, IVD aluminum benchmark, and acid Zn-Ni alloy coatings with the vendor recommended and applied post-treatment (conversion coating) the overall performance was better than with the trivalent chromium (NAVAIR TCP) post-treatment. In contrast to this, the ternary Zn-Ni-based coatings exhibited better overall performance with the trivalent chromium conversion coating. Consequently, the utility of the post-treatment may be dependent on coating composition, and needs further study.

Of the limited number of alternative coating systems reported here, the alkaline Zn-Ni alloy coating exhibited the best performance and could be a candidate for implementation if its lubricity, fatigue, and other properties are equivalent to or better than those for electroplated cadmium coatings. Other projects are, or will be investigating these performance requirements before a final decision is made.

Disclaimer

The results presented here are based on coatings applied by a number of different vendors/suppliers. Every effort was made to provide a fair comparison between the coatings investigated. However, while the results presented here enable a comparison to be made for the conditions described, alloys with different compositions and/or post-treatments, or subjected to different test conditions, may exhibit different performance characteristics. In no way are the findings from this investigation meant to be an endorsement or criticism of a particular vendor/supplier or coating system.

REFERENCES

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