Evaluation of Zinc Alloys As An Alternative to Cadmium

John T. Stropki, BATTELLE and
Glen H. Graham, CEF, OC-ALC/LPPNP, Tinker AFB

Abstract

The Oklahoma City--Air Logistic Center's plating shop discontinued cadmium plating in November 1991. Three substitutes for cadmium plating were chosen to cover all current applications of electroless nickel plating, ion-vapor-deposited aluminum, and alkaline zinc-nickel. At that time there was not sufficient data to fully support this decision. Test data have since been verified that the solution chosen was the best for aerospace applications. This paper presents test results for all major areas of concern, including fatigue debit and hydrogen embrittlement, to validate the choice of the alkaline zinc-nickel as opposed to the other zinc alloys available.

Background

Fasteners and components manufactured from low- and high-strength steel alloys have been historically cadmium-plated for military hardware to provide corrosion protection and galvanic compatibility with aluminum alloys. In recent years cadmium has been targeted as a toxic metal that should be eliminated from plating requirements, especially by the Air Force. A joint task group of Army, Navy, Air force, Marines, and Coast Guard met in May of 1989, and began efforts to minimize or eliminate cadmium, chromium, and cyanides from the work area.

At Oklahoma City-Air Logistics Center (OC-ALC) cadmium was targeted for elimination actually in 1987 when an Ion Vapor Deposited Aluminum (IVDAI) unit was installed for this purpose. The IVDAI coating was never fully implemented since the cadmium plating was still available, and because of the imitations of an IVDAI coating for threaded areas and internal diameters. By 1991 it became apparent that some action needed to be taken to bring the elimination of cadmium in focus. By this time the automotive industry had made strides in cadmium elimination through the use of zinc alloys, and electroless nickel plating has been used for corrosion protection for years. With this data available, the Directors of Propulsion and Environment at OC-ALC had the plating shop discontinue the plating of cadmium in November, 1991.

The Material Management sector at OC-ALC, given the available data for corrosion protection requested that zinc-nickel plating be installed at OC-ALC's plating shop. From the available information on zinc-nickel coatings the Process Engineering section plating engineers chose to use an alkaline zinc-nickel bath. The alkaline zinc-nickel bath was placed in the cadmium plating tanks in February of 1992 and was in full production in three days.

However, at that time there were not sufficient data to fully support this decision for aerospace applications. OC-ALC entered a contract with Battelle to obtain the test data verification that the solution chosen was the best for aerospace applications. This paper gives the test results for all major areas of concern including fatigue debt and hydrogen embrittlement to validate the choice of the alkaline zinc-nickel as opposed to the other zinc alloys available.

Since cadmium is a toxic metal and on the EPA's Industrial Toxics Project for voluntary reduction on Tinker AFB's Environmental Management Office (OC-ALC/EMV), this project was funded to validate that the alkaline zinc-nickel plating was the best substitute plating for cadmium. This objective was achieved by reviewing all available data and technical information published on zinc alloy plating systems and conducting laboratory validation tests in comparison with cadmium. The information collected will be presented in this paper and is being used by OC-ALC for their applications.

Technical Approach

A review of the materials, instrumentation and protocol used in performing this study are detailed in the following text.

A Test Plan was drafted at the initiation of the study. This plan was used to detail an outline of the various laboratory tests which were considered necessary for (1) demonstrating the validity of using a zinc alloy (alkaline zinc-nickel) plating process as a replacement for cadmium plating, and (2) compar atively evaluating the performance quality of various acid and alkaline zinc alloy (Zn-Ni, Zn-Co, Zn-Sn, and Zn-Fe) plating processes.

An extensive literature search and review of zinc alloy plating data and technical information contained within journals and other publications was performed as a part of this study. Vendors, chemical companies, government and industrial research laboratories, as well as large volume users (e.g., Boeing, GE, Ford, General Motors, MasterLock) of both cadmium and zinc alloy plating processes were contacted in an effort to develop a database which included the following:

- Specific application(s) for the cadmium and zinc alloy plating processes,
- Plating conditions for optimal thickness, uniformity, density (low porosity), corrosion and wear resistance,
- Available laboratory and service data on corrosion, fatigue, hydrogen-stress cracking and torque-tension.

Information collected during this task provided engineers with technical insight into each of the plating processes, which was essential to identifying the optimal operating ranges (chemistry, current density, temperature) for the baths. This optimization process maximized the as-deposited quality of the various platings. The collection of this information also allowed for the proper selection of plating shops which were responsible for electrodepositing the appropriate coatings on the various test specimens. Specimens plated with a commercially available alkaline Zn-Ni electrodeposit were prepared by the vendor and OC-ALC/LPPNP process engineers at Tinker AFB, OK.

Information compiled during this task was also used to supplement the results obtained from a similar set of validation testing performed on an acid Zn-Ni plating systems by personnel at Hill AFB, UT.

Experimental Procedures

Testing was designed to compare the zinc alloy electrodeposit with the actual service requirements of steel aircraft component parts (nuts, bolts, brackets, plates, and flap tracks) which are cadmiunplated by OC-ALC/LPPNP personnel at Tinker AFB, OK.

A variety of American Society for Testing and Materials (ASTM) test methods and standards were used to comparatively assess the corrosion resistance, wear resistance, fatigue loss, and hydrogen-stress-cracking (HSC) susceptibility of high-strength steel plate and rod specimens coated with cadmium and various acid and alkaline zinc alloy electrodeposits. Non-standardized tests were used to define the torque-tension relationships for low-strength steel fasteners that also were plated with each of the above mentioned electrodeposits.

Whenever possible, the individual test coatings were applied at the same thicknesses as those listed in the appropriate cadmium application specifications (QQ-P-416 or MIL-STD-870B). Specifically, the nominal thickness of all coatings on test panels was 0.0005 inch (0.5 mil). The coating thickness for threaded fasteners was specified at 0.0003 inch (0.3 mil).

The plating systems that were evaluated in each set of validation tests included:

1. Cadmium - alkaline bath
2. Zinc/Cobalt - acid and alkaline bath
3. Zinc/Tin - alkaline bath
4. Zinc/Iron - alkaline bath
5. Zinc/Nickel - acid and alkaline bath.

Most of the zinc alloy test coatings and the cadmium-plated experimental control specimens were post-treated with chromic-acid based passivating solutions. For comparison purposes, a single set of cadmium-plated specimens were processed without the chromic acid treatment. These specimens were considered the baseline control specimens.

A summary of the laboratory tests and pre-post-test plating evaluations that were performed during this study is provided in the following text.

Corrosion

Corrosion testing was performed to determine the corrosion resistance of the various electrodeposits. All results were compared with a baseline set of specimens that were cadmium-plated and not passivated with a post-plate chromic acid treatment.

Four 6.0-inch by 4.0-inch by 0.25-inch AISI 4340 steel panels that were heat-treated to a hardness of $R_c > 50$ were plated with each of the plating systems. The nominal thickness of all electrodeposits was 0.0005 inch (0.5 mil).

Testing protocol included coating two panels from each plating group with one coat of MIL-P-85582 epoxy primer. The thickness of the coating ranged between 0.0006 inch and 0.0009 inch (0.6 mil and 0.9 mil). The coatings on these panels were allowed to cure at room temperature for seven days. When cured, a large X was scribed on one side of a single primed panel, as well as on one side of an unprimed panel from each plating group. All scribes were made using a scribing tool and the procedures referenced in ASTM D1654 (Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments).

In accordance with the specifications in ASTM B117 (Salt Spray (Fog) Testing), all panels were then positioned on a plastic rack and exposed in a neutral salt (5 percent NaCl) fog test chamber. All specimens were visually inspected on a daily basis. Time to the first visible sign of (1) white corrosion products and (2) red was recorded for all panels. Testing was terminated after 1,000 hours or whenever all specimens failed, whichever occurred first.

Abrasion

An abrasion test was conducted to determine the ability of the various electrodeposits to protect a steel substrate from wear or abrasion damage. Results collected for all coatings were compared with the data obtained for the non-passivated and passivated (chromic acid) cadmium-plated test specimens.

Test specimens were laser cut from AISI 4340 steel plate and had nominal dimensions of 4.0 inches OD by 0.25 inch thick. All surfaces were prepared by rotary sanding with 60 grit emery paper, then grit blasting with 100 μ garnet. This procedure produced a surface roughness in the range of 80 to 100 μinch. This particular finish was comparable to a finish found on typical aircraft component parts prior to plating as reported by maintenance personnel at Tinker AFB, OK. A 0.250-inch hole was drilled into the center of each specimen. After machining, the specimens were cleaned and plated in duplicate with cadmium and the respective zinc alloy coatings in accordance with MIL-STD-870 or applicable vendor specifications. The desired thickness for each plating was 0.0005 inch (0.5 mil).

A standard Model 503 Taber Abraser was used to conduct all wear tests. Testing included CS-17 Calabrase disks, and a load of 1000 grams. Abrasive wheel cleaning with 50 revolutions on S-11 cleaning disks was performed at 2000 cycle intervals. New CS-17 disks were used for each type of plating. Periodic visual inspection combined with compositional measurements using an energy dispersive analysis of x-rays (EDS) system was used to identify the time of wear-through.

After all testing, the individual sample disks were examined in cross-section to quantify coating thickness. A normalized wear rate, in cycles per mil, was obtained by dividing the number of cycles by the coating thickness.

The completion of a wear test was defined by wear-through of the coating over half the wear track width.

Fatigue

Fatigue tests were performed to compare the fatigue properties of the zinc alloy coated specimens with both the plated and unplated cadmium specimens to determine the potential for reduction in fatigue life.

Specimens were fabricated from AISI 4340 steel that was heat-treated to a nominal ultimate tensile strength of 260,000 to 280,000 psi in accordance with the requirements of MIL-H-68754.

Specimens tested machined with a circular cross-section to the specifications of ASTM E466, *Standard Practice for Conducting Constant Amplitude Axial Fatigue Tests of Metallic Materials*. The specimens were machined with tangentially blending fillets between the test section and the grip ends. The diameter of the test section was 0.3125 inch, and the diameter of the grip ends was 0.625 inch. Therefore, the cross-sectional area of the grip was four times that of the test section, as specified by ASTM E466. The blending fillet radius was 3.75 inches, which is 12 times the diameter of the test section. ASTM E466 recommends a fillet radius at least eight times the diameter of the test section. The length of the test section was 1.875 inches or six times the test section diameter. ASTM E466 requires a test section length of at least three times the diameter for tensile fatigue loading. The surface finish of the machined specimens, prior to plating, was measured at 15 μin.

To determine the ultimate tensile strength of the test specimens and to verify the heat treatment, tests were conducted using specimens randomly selected from the two lots fabricated for plating and fatigue testing. The tensile tests were conducted in accordance with ASTM E8, *Standard Test Methods of Tension Testing of Metallic Materials*. A minimum of three valid tests was conducted. A valid test was determined to be one in which the failure occurred within the test section. The average ultimate tensile strength of a group of specimens was 263,700 psi with a standard deviation of 830 psi. This tensile strength falls within the range targeted by MIL-H-6875H. The failure mode associated with each of the tensile tests was a classical cup-cone fracture.

The fatigue tests were conducted in accordance with ASTM E466, *Standard Practice for Conducting Constant Amplitude Axial Fatigue Tests of Metallic Materials*. All fatigue tests were conducted under load control with a positive stress ratio. The initial tests were conducted under tension-tension loading at a stress ratio of R=0.1 and a frequency of 15 Hz. Tests also were conducted at a stress ratio of R=0.43 for comparison with data generated at Hill AFB.

Hydrogen Stress Cracking

This test was selected to determine the susceptibility of each plated material to hydrogen-stress cracking (HSC).

A set of notched, round, button-ended tensile bar specimens were used to conduct all HSC testing. All bars were manufactured from AISI 4340 steel (MIL-S-5000) and heat treated to obtain an ultimate tensile strength (UTS) between 260 and 280 ksi in accordance with MIL-H-6875F. Average notched-bar tensile strengths of unplated specimens from the two lots of AISI 4340 steel that were evaluated during this program are as follows:

Lot Number	No. of Specimens	Average Notched-Bar Tensile Strength, ksi
1	10	370.3
2	3	357.0

The 0.2 percent yield strength of this material was at least 80 percent of the UTS.

All test specimens were machined to the dimensions required for a typical Type 1a round tensile specimen described in ASTM F519.

Post-machining dimensions of the specimens and applicable heat lot acceptance criteria (hardness and notch surface quality) were verified prior to electroplating.

Cadmium and the various zinc alloys were electroplated onto the surfaces of the individual test specimens by commercial electroplating companies. After plating, the specimens were baked in an ove-nat 375°F for a minimum of 23 hours, removed from the furnace, wrapped in paper folders, and stored in a desiccator until the initiation of testing.

All test specimens were individually loaded into screw-loaded tensile machines to 45 percent of their notched-bar tensile strength (NTS). Timers controlled with miniature microswitches were used to record the failure times of all specimens. Testing was discontinued if a specimen did not fail within 200 hours. A minimum of three specimens was evaluated for each plating system.

Torque-Tension

The torque-tension test was used to determine the torque required to achieve a given axial load on threaded fasteners used to assemble aircraft structures. Representative fasteners were plated with cadmium and the zinc alloys being evaluated.

Test specimens consisted of threaded 5/16-inch fasteners that were recommended by OC-ALC/LPP-NP personnel. Individual fasteners were of a composition similar to AISI 8740 steel. Fasteners were plated with cadmium and the zinc alloy coatings to a thickness of 0.0003 inch (0.3 mil) and tested in accordance with MIL-STD-1312/15. All plated and chromated specimens were relief baked at 375°F for a minimum of 23 hours prior to being cleaned and tested.

A lubricant specified in MIL-T-5544 was used to lubricate the threads of all plated bolt specimens.

For each group of plated test specimens, an axial load was determined at torque values that were calculated for the specified fastener size. The torque values for fasteners used during this task are expected to range from 100 to about 300 inch-pounds. Personnel at Brigham Young University (BYU) were responsible for all testing and data analysis. BYU has developed a computerized methodology for performing all testing.

Axial load was determined at 100 percent of the identified torque on each nut application cycle. A torque required to produce 5500 pounds of tensile force was applied to the fasteners. All torque and tension measurements for the zinc alloy plated specimens were compared with the data collected for the cadmium-plated specimens.

Experimental Results

Process Evaluation

Substrate Qualification

Fatigue and HSC testing of the high-strength AISI 4340 steel confirmed a need to examine the pre-plate surface condition of test specimens because of an increased sensitivity to surface finish and electrodeposition processes. Concerns related to the preparation of the substrate were investigated and discussed with OC-ALC/LPPNP and OO-ALC-/LIPEP personnel prior to plating the fatigue and HSC test specimens.

A second surface preparation process that is considered a source of problems for the medium-to-high (180 to 260 ksi) strength steels plated with the zinc alloys is a reverse etch chemical cleaning process. This process which includes a reverse etch cleaning followed by an acid pickling should not be used on specimens that are plated with the zinc alloy electrodeposits. This process introduces surface cracks into the substrate (AISI 4340 steel) prior to a plating with the respective alkaline zinc alloy deposits. These cracks and the subsequent electrodeposition processing significantly reduce alloy deposits of the fatigue life and HSC resistance of this material.

Plating Process Qualification

Coating Adhesion

A requisite for good adhesion of any protective zinc-alloy coating process is proper substrate preparation and cleaning. Procedures recommended for use with the zinc-alloy deposits are almost identical to the procedures specified for the cadmium electrodeposition process. Both processes are adequate for superior service performance of low-strength steel aircraft components if accomplished in accordance with the requirements of QQ-P-416 and MIL-STD-870B. A special set of substrate preparation requirements, similar to those provided in MIL-C-1501C and QQ-C-320B, must be used for high-strength (greater than 220 ksi) steel components. These requirements include a grit (80 to 120-grit aluminum oxide or garnet) blasting per MIL-STD-1504 of the surfaces to be plated, followed by a thorough rinse.

Coating Coverage, Uniformity, and Thickness

A microscopic and metallographic analysis of several plated components confirmed that the throwing power efficiency of the alkaline zinc-nickel plating processes was adequate. The surface morphology (density, uniformity and compactness) of the alkaline zinc-nickel deposits on panels that were plated per OC-ALC/LPPNP requirements appeared to be superior to similar panels plated by the vendor of the alkaline Zn-Ni process evaluated during this study. The reason for this difference may be related to the specific pre-treatment preparation techniques used by the two plating shops.

Representative structures of the various zinc-alloy deposits were examined in the scanning electron microscope (SEM). The discussion for this paper will concentrate on the zinc-nickel alloys. The surface topography of the alkaline zinc-nickel deposits clearly shows a compact clustering of nodular shaped grains that varied in size. The deposits produced by both the vendor and OC-ALC-/LPPNP had a fine-grained texture which is controlled by the Zn-Ni ratio, as well as bath temperature and age. The type and concentration of additives in the respective plating baths also controls the as-deposited texture and quality of the deposit.
Examinations conducted on flat rod and threaded components confirm that the zinc-nickel deposition processes are not limited by line-of-sight coverage and do have the potential of producing coating thicknesses greater than 0.001 inch. These examinations also confirmed negligible coating build-up or run-off at the sharp and rounded edges of specimens. This result has also been experienced in laboratory and service trials conducted by both industrial and military laboratories.

In general, deposition of a thicker coating of any zinc-alloy deposit will contribute to an increase in corrosion resistance and a decrease in coating uniformity. Thicker coatings should be avoided on the higher strength materials because of the increased susceptibility to HSC.

Surface Smoothness

The smoothness of the zinc-alloy deposits is dependent on substrate surface condition and/or preparation, coating thickness and adherence. The type and quality of post-plate treatment applied to the coated component also influences the smoothness of the deposit.

In general, the various zinc-alloy and cadmium electrodeposits replicate the surface finish of a coated substrate. The effect on surface smoothness of 0.0005-inch-thick or less zinc alloy or cadmium finishes is considered negligible. Surface smoothness of the zinc-alloy coatings decreases as coating thickness increases.

Temperature

Service temperature is of importance for the deposit selected as a replacement for cadmium. For this study, the influence of temperature on plated components was limited to the zinc-nickel deposits.

Cadmium transforms from a solid to a liquid at 610°F; however, the service temperatures for cadmium-plated steel components are limited to 450°F because of a plated components susceptibility to liquid metal embrittlement (LME). Specifically, the onset of embrittlement has been observed for plated and notched AISI 4340 steel at temperatures as low as 450°F.

Information in an American Society of Metals (ASM) handbook (No. 13) suggests that AISI 4340 steels will embrittle from contact with zinc at temperatures ranging between 600°F and 700°F. This range may be higher or lower depending on (1) the contribution of the nickel and (2) other contaminant elements with lower melting points that may be in the zinc-alloy deposit. Therefore, it is recommended that components plated with zinc-nickel deposits not be exposed to continuous temperatures in excess of 700°F. Elevated temperature tensile testing would be required before the coating process is recommended for engine-related parts (e.g., bolts, hangers landing gear assemblies, tie rods) that might be continuously exposed to 800 to 900°F service temperatures.

Performance Evaluation

An analysis of the experimental data collected from the various laboratory tests performed on the zinc-alloy deposits confirms the following results.

Corrosion

Results obtained from the ASTM B117 neutral salt fog testing are provided in Table 1. The data indicate that the corrosion resistance of the alkaline zinc-nickel specimens plated by the vendor of the process is superior to cadmium-plated specimens. No white rust or corrosion products were observed on the scribed and/or non-scribed surfaces of the alkaline zinc-nickel specimens that were chromate conversion coated prior to testing.

After 1008 hours of exposure to the neutral salt fog environment, the plated surfaces of the alkaline zinc-nickel specimens contained no corrosion products. White rust was detected on the scribed and non-scribed cadmium (chromated)-plated specimens after 504 hours and 672 hours, respectively. This result compares to localized white rust deposits being observed in the scribe of the cadmium (non-chromated)-plated specimens after only 168 hours of exposure. No red rust was detected on the surfaces of either set of cadmium-plated specimens or the alkaline zinc-nickel plated specimens. Other test data from this project confirm the improved corrosion resistance of these plated materials if an epoxy primer is applied over a quality chromate conversion coated component.

A second zinc-alloy deposit that displayed excellent corrosion resistance during this study is the alkaline zinc-tin coating. The results obtained for the scribed and non-scribed specimens were similar to the results obtained for the non-chromated cadmium-plated specimens.

Red rust deposits were noted on the surfaces of all other zinc-alloy coated specimens at some interval of testing. The poorest performing coating system was the acidic zinc-nickel deposit. The suspected sources of the premature corrosion observed on the scribed and non-scribed specimens are the (1) low concentration (~ 2 percent) of nickel in deposit, (2) poor coating uniformity, and (3) degree of cracking noted throughout the "as-deposited" coating and along the coating-to-substrate interface.

Abrasion

Normalized wear rates obtained for all zinc alloy coatings are shown in Figure 1. For this study, a mathematical normalization of all wear rates was required because of the variability associated with deposit thicknesses. The normalization formula assumed a linear relationship between deposit thickness and wear resistance. The wear rate was defined as the number of cycles required to wear through the coating over half of the wear track, normalized to a one mil (0.001-inch) coating thickness.

Based on the normalized data, the acidic zinc-nickel, alkaline zinc-nickel and alkaline zinc-cobalt deposits provided the greatest wear resistance. These coatings were abraded for 50,000 to 70,000 Taber Abraser cycles without exposing the steel substrate. Based on the observed cadmium control coating failure after ≈ 32,000 cycles, testing of this coating was arbitrarily terminated after 34,000 cycles.

Fatigue

An initial set of tests were conducted on unplated specimens (FT) at various load levels to determine a stress level at which the unplated specimens achieved a fatigue life of approximately one-half-million cycles. As shown in the test results provided in Table 2, an average fatigue life of 242,450 cycles was achieved while testing at a maximum load of 12,760 pounds which represents 58 percent of the ultimate tensile strength of the steel alloy substrate.

Additional test results for the cadmium-plated specimens and specimens coated with the two different zinc-nickel alloys are provided in Table 2. As shown, tests were conducted at stress ratio's of (1) R = 0.1 and a maximum tensile load of 12,760 pounds, and (2) R = 0.43 and a maximum tensile load of 15,400 pounds . The fatigue life for the cadmium plated specimens at the R = 0.1 ratio is approximately three times higher than the average life of the unplated specimens. An even higher fatigue life is noted for the single set of alkaline zinc-nickel specimens (TK) that were plated at Tinker AFB, OK. This increase of fatigue life is attributed to the surface preparation procedure for the cadmium plating process. Specifically, all specimens were grit-blasted using an 80- to 120-mesh garnet grit prior to plating. This blasting process introduces compressive residual stresses near the surface of the material and the ductile cadmium and zinc-nickel platings allowed the fatigue failures to originate from within the base metal. While compressive residual stresses were not quantified, their affect in increasing fatigue life is suggested by these results.

The effect of compressive residual stresses on fatigue life discussed in the previous text was not evident with a single set of specimens (HL) that were plated with the acid zinc-nickel deposit at Hill AFB. However, it should be noted that these specimens were tested under tension-tension loading at a maximum load of 70 percent of the ultimate tensile strength and a minimum load of 30 percent, yielding a stress ratio of R = 0.43. These conditions were selected for a comparison with fatigue test data generated at Hill AFB, UT.

The Hill test conditions were used on cadmium and alkaline zinc-nickel-plated specimens. The results obtained from these tests suggest that the fatigue life for the cadmium and zinc-nickel (acid and alkaline) deposits are similar.

Pre-plate chemical surface preparation techniques that were used on a set of alkaline zinc-nickel (ZNL) and acid zinc-nickel (ZNC) specimens are not recommended for high-strength steel alloys. This process introduces surface defects or stress risers into the substrate that significantly reduce the fatigue life of the specimens.

The results of fatigue testing conducted on the remaining zinc alloy deposits at a stress ratio of R = 0.1 indicate that the alternative processes reduce the fatigue life of the AISI 4340 steel. These processes are not recommended for high-strength steel components.

Hydrogen Stress Cracking

The results of sustained load tests of the specimens from Lot 1 of the AISI 4340 steel are listed in Table 3. These results show that the cadmium electroplating processes, with and without the chromate conversion treatment, and the alkaline zinc-nickel were the only electroplating processes that were determined to be non-embrittling using the criterion set forth in Paragraph 9.4 of ASTM Designation F-519. In addition, the unplated AISI 4340 steel specimens did not fail within the 200-hour runout period.

All of the other candidate electroplating processes resulted in hydrogen-stress-cracking failures in all of the high strength AISI 4340 steel specimens. Several of the specimens failed while they were being loaded (0 hours exposure time) and the others failed in times ranging from 0.2 to 8.3 hours.

A second set of notched tensile specimens fabricated from AISI 4340 steel were electroplated using the (1) alkaline zinc-nickel process at Tinker AFB, and (2) acid zinc-nickel process at Hill AFB. These specimens along with unplated specimens were subjected to the sustained-load tests at applied stresses equal to 75 percent of the average notched-bar tensile strength of unplated specimens. The results of those sustained load tests are listed in Table 3.

The results of the sustained-load tests of the unplated and electroplated specimens revealed that all of the specimens survived the 200-hour runout period. Thus, the alkaline zinc-nickel electroplating process used at Tinker AFB and the acid zinc-nickel electroplating process used by Hill AFB did not cause hydrogen-stress cracking in the high strength AISI 4340 steel specimens. The criteria in ASTM E519 for acceptance of a process to be nonembrittling are:

1. If none of the specimens fracture within the exposure time (200 hours), the process shall be considered nonembrittling.
2. If only one of a minimum of three specimens fractures within the exposure time, retest the material or process with three unused specimens and if no fracture occurs within the exposure time, the material or process shall be considered nonembrittling. If any specimen fractures during retest, the material or process shall be considered embrittling.
3. If two or more specimens fracture within the exposure time, the material or process shall be considered as having excessive embrittling characteristics.

Using those criteria, the results of this study have shown that for AISI 4340 steel specimens, the plating processes that were nonembrittling or embrittling were as follows:

Non-Embrittling	Embrittling
Alkaline zinc-nickel	Acid zinc-nickel (Process B)
Acid zinc-nickel (Hill AFB)	Acid zinc-cobalt
Cadmium plus chromated	Alkaline zinc-cobalt
Cadmium	Alkaline zinc-iron
	Alkaline zinc-tin

Torque-Tension

The excellent lubricity of cadmium on threaded fasteners has been well documented. The low coefficient of friction is one of the most unique surface properties of this coating.

A review of the test results recorded for all zinc-alloy plated fasteners evaluated during this program was performed. In summary, the deposits that appear to give the most consistent results (i.e., smallest decrease between Test 1 and 15), determined from the averages and standard deviation of the test runs, were found to be acidic zinc-nickel and alkaline zinc-iron.The least consistent plating process was cadmium chromate, based on the limited number of fasteners tested. Fastener assemblies that experienced similar breaking torques included the alkaline zinc-nickel and cadmium (chromated and non-chromated) deposits. The lowest breaking torques were measured for the acidic zinc-nickel and acid/alkaline zinc-cobalt coatings. High breaking torques (greater than 140 inch per pounds) were measured for the alkaline zinc-iron and alkaline zinc-tin coatings. These results indicate that a similar torque was required using alkaline zinc-nickel and cadmium-finished fasteners when the torque was applied to fasteners with identically plated, nonlocking lubricated nuts.

Conclusions

The test data obtained from this study indicate that the alkaline zinc-nickel plating meets or exceeds cadmium plating in all areas. The choice of this plating for aerospace applications was a valid option and will continue to be used at OC-ALC.

References

1. Graves, B.A., "Industrial Toxics Project: The 33/50 Program", *Products Finishing* 56 No. 9, 132 (1992).
2. Lesser, E.H., "Alternatives to Cadmium Plating: Reflections Five Years Later", *Plating & Surface Finishing*, 69 No. 11, 34-43 (1982).
3. Natorski, T.J., "Zinc and Zinc Alloy Plating in the 90's", *Metal Finishing*, 90 No. 3, 15-17 (1992).
4. Loar, G.W., Romer, K.R., and Aoe, T.J., "Zinc-Alloy Electrodeposits for Improved Corrosion Protection", *Plating and Surface Finishing*, 78 No. 3, 74-79 (1991).
5. Sizelove, R.R., "Developments in Alkaline Zinc-Nickel Alloy Plating", *Plating and Surface Finishing*, 78 No. 3, 26-30 (1991
6. Dini, J.W., and Johnson, H.R.,"Electrodeposition of Zinc-Nickel Alloy Coating", *Proc. Workshop Alt. Cadmium Electroplat. Met. Fin.*, Gaithersburg, MD, Oct. 4-6, 1977, 34-5, 1979. 11. Albalat, R. et al., "Zinc-Nickel Coatings: Relationship Between Additives and Deposit Properties", *Journal of Applied Electrochemistry*, 21 44-49 (1991).
7. Gomez. E. et al., "A Zinc-Nickel Electroplating System", *Metal Finishing*, 90 No. 6, 87-91 (1992).
8. "CorroBan - The Boeing Zinc-Nickel" Technical Bulletin from Pure Coatings Company, 3301 Electronics Way, West Palm Beach, FL 33407.

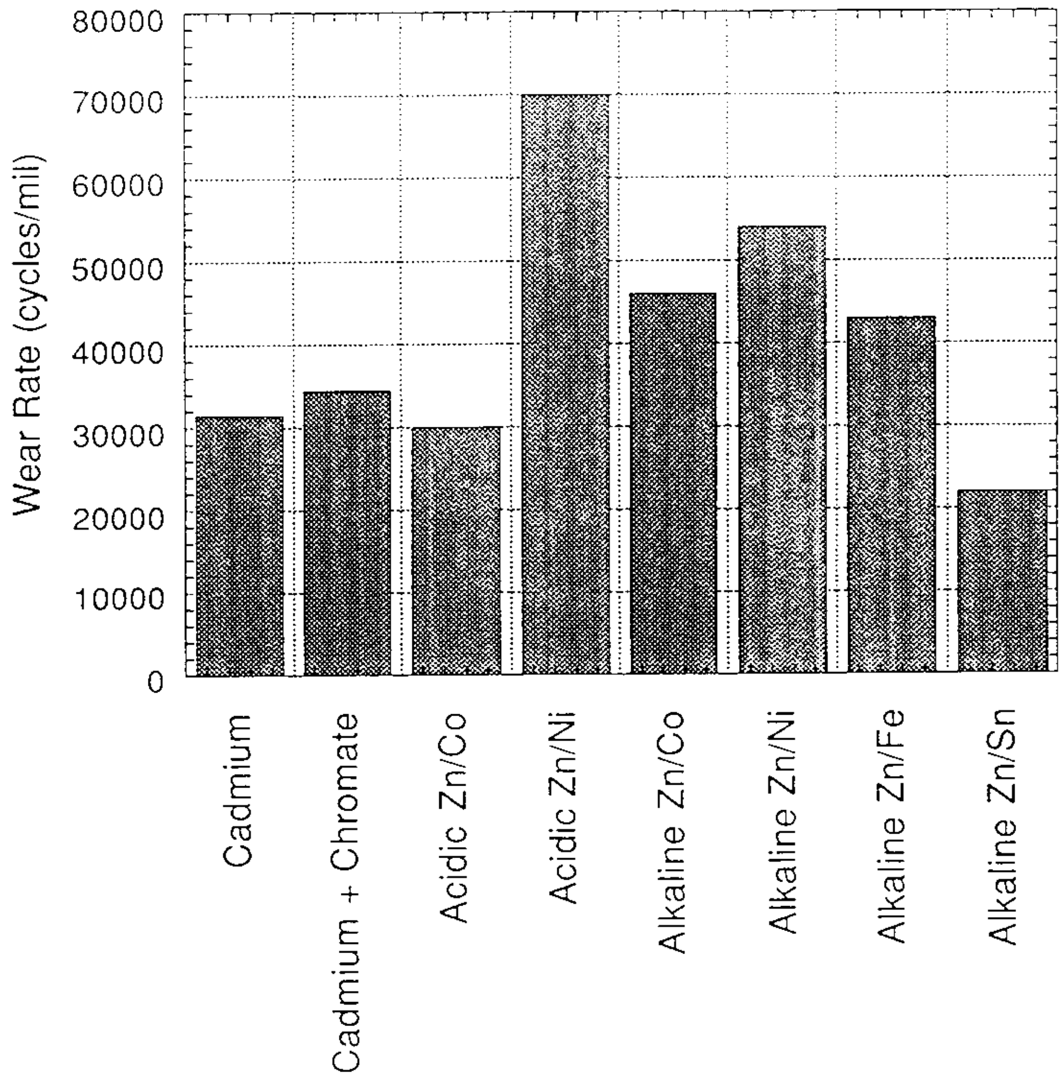

Figure 1. Wear rates calculated for coated test specimens
Note: All rates normalized to 0.0001 inch or 1.0 mil.

Table 1. Results of ASTM B117 salt fog corrosion testing conducted on coated test specimens

Note: WR = White Rust Deposits
RR = Red Rust Deposits

Coating	Panel Condition	Exposure Period, hours					
		168	336	504	672	840	1008
Cadmium (chromated)	Scribed Non-Scribed	-- --	-- --	WR --	WR WR	WR WR	WR WR
Cadmium (non-chromated)	Scribed Non-Scribed	WR --	WR --	WR --	WR WR	WR WR	WR WR
Zinc Nickel (acid)	Scribed Non-Scribed	WR WR	RR RR	RR RR	RR RR	RR RR	RR RR
Zinc Nickel (alkaline)	Scribed Non-Scribed	-- --	-- --	-- --	-- --	-- --	-- --
Zinc Iron (alkaline)	Scribed Non-Scribed	WR WR	WR WR	WR RR	RR RR	RR RR	RR RR
Zinc Tin (alkaline)	Scribed Non-Scribed	WR --	WR --	WR --	WR WR	WR WR	WR WR
Zinc Cobalt (alkaline)	Scribed Non-Scribed	WR WR	WR RR	RR RR	RR RR	RR RR	RR RR
Zinc Cobalt (acid)	Scribed Non-Scribed	WR --	WR WR	RR WR	RR RR	RR RR	RR RR

Table 2. Results of fatigue testing conducted on coated test specimens

Material Set No.	Plating Type	Stress Ratio	Maximum Stress, ksi	Maximum Strength, percent	Maximum Load, kip	Average Fatigue Life, cycles	Standard Deviation of Fatigue Life, cycles	Samples
1	Unplated (FT)	0.1	166.4	58	12.76	242,456	239,842	3
1	Cadmium (CDL) w/chromate	0.1 0.43	166.4 200.8	58 70	12.76 15.4	760,038 40,452	172,233 33,284	8 4
1	Cadmium (CCL) w/o chromate	0.1 0.43	166.4 200.8	58 70	12.76 15.4	730,733 run-out	259,381 N/A	10 5
1	Alkaline Zn-Ni McGeon-Rohco (ZNL)	0.1 0.43	166.4 200.8	58 70	12.76 15.4	9,941 11,911	1,155 1,299	8 4
2	Alkaline Zn-Ni Tinker AFB (TK)	0.1 0.43 0.43	152.9 184.5 200.8	58 70 76	11.725 14.15 15.4	run-out run-out 42,311	N/A N/A 13,225	1 4 3
1	Acid Zn-Ni Lancaster (ZNC)	0.1 0.43	166.4 200.8	58 70	12.76 15.4	15,262 5,438	13,266 238	8 4
2	Acid Zn-Ni Hill AFB (HL)	0.43	184.5	70	14.15	39,819	2,388	4
1	Acid Zn-Co (ZCC)	0.1	166.4	58	12.76	7,459	1,288	11
1	Alkaline Zn-Co (ZCL)	0.1	166.4	58	12.76	22,521	9,076	11
1	Alkaline Zn-Sn (ZSL)	0.1	166.4	58	12.76	19,717	7,620	11
1	Alkaline Zn-Fe (ZFL)	0.1	166.4	58	12.76	30,953	14,273	10

Table 3. Results obtained from hydrogen-stress-cracking (HSC) tests
All specimens were loaded to applied stresses equal to 75 percent
of the overage notched-bar tensile strengths of the unplated specimens

Specimen Identification	Type of Coating	Test Exposure Period, hrs	Results
205A	Unplated	217.7	Passed
206A	Unplated	216.7	Passed
218A	Unplated	215.7	Passed
242A	Cadmium - Chromated	183.5	Failed
244A	Cadmium - Chromated	262.6	Passed
252A	Cadmium - Chromated	262.4	Passed
256A	**Cadmium - Chromated**	**258.0**	**Passed**
251A	**Cadmium - Chromated**	**215.4**	**Passed**
238A	**Cadmium - Chromated**	**215.7**	**Passed**
227A	Zinc-Nickel (Alkaline)	141.1	Failed
203A	Zinc-Nickel (Alkaline)	258.0	Passed
233A	Zinc-Nickel (Alkaline)	259.5	Passed
253A	**Zinc-Nickel (Alkaline)**	**213.5**	**Passed**
260A	**Zinc-Nickel (Alkaline)**	**213.5**	**Passed**
255A	**Zinc-Nickel (Alkaline)**	**213.4**	**Passed**
257A	Zinc-Cobalt (Alkaline)	4.5	Failed
210A	Zinc-Cobalt (Alkaline)	4.5	Failed
202A	Zinc-Cobalt (Alkaline)	8.3	Failed
200A	Zinc-Cobalt (Acid)	0.8	Failed
204A	Zinc-Cobalt (Acid)	5.7	Failed
209A	Zinc-Cobalt (Acid)	4.4	Failed
231A	Zinc-Iron (Alkaline)	0.0	Failed
201A	Zinc-Iron (Alkaline)	0.4	Failed
246A	Zinc-Iron (Alkaline)	1.6	Failed
230A	Zinc-Tin (Alkaline)	0.2	Failed
223A	Zinc-Tin (Alkaline)	0.0	Failed
224A	Zinc-Tin (Alkaline)	0.0	Failed
262A	Zinc-Nickel (Acid)	0.5	Failed
219A	Zinc-Nickel (Acid)	0.5	Failed
249A	Zinc-Nickel (Acid)	0.4	Failed
248A	Cadmium (No Chromate)	213.4	Passed
237A	Cadmium (No Chromate)	213.4	Passed
259A	Cadmium (No Chromate)	213.3	Passed

Table 4. Results of sustained load tests of unplated and electroplated specimens from (Tinker AFB [alkaline Zn-Ni] and Hill AFB [acid Zn-Ni]).

All specimens loaded to 267.8 ksi, 75 percent of the notched-bar tensile strength of the unplated specimens

Electroplating Process	Test Duration, hours	Result
Unplated	242.0	passed
Unplated	241.7	passed
Unplated	241.8	passed
Acid Zinc-Nickel	240.4	passed
Acid Zinc-Nickel	240.4	passed
Acid Zinc-Nickel	240.0	passed
Alkaline Zinc-Nickel	239.9	passed
Alkaline Zinc-Nickel	240.8	passed
Alkaline Zinc-Nickel	238.6	passed