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Evaluation of Alternatives to Electrodeposited Cadmium for Threaded Fastener Applications

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ABSTRACT

Cadmium (Cd) plating offers good corrosion resistance, lubricity, solderability, adhesion, and ductility, as well as consistent torque-tension and uniform thickness on components with complex geometries. However, the intrinsic Environmental, Health, and Safety issues associated with Cd have driven many users to seek alternatives. Currently, various Cd replacement teams/programs such as the Joint Group on Pollution Prevention (JG-PP)/Boeing, the Joint Cadmium Alternatives Team (JCAT), the Canadian Cadmium Replacement Program (CCRP), and the REFOCUS Program (AEA Technology, European) have been investigating alternatives to Cd plating. Some of the current coatings being considered in the aerospace industry include Zn-Ni alloy plating, electrodeposited aluminum, electroless nickel, nickel composite, and molten salt aluminum manganese (Al-Mn). Each option has its own particular characteristics; however, most experiments have been conducted on aerospace structural panels or components. There is a need to evaluate various alternative coatings for complex geometries such as threaded fasteners.

To this end, Lockheed Martin Aeronautics and Alcoa Fastening Systems have teamed to evaluate Cd alternatives for threaded fasteners used in the inlet of F-16 aircraft. One F-16 manufacturing process generates Cd dust from the fastener heads during sanding. The United States Air Force has funded Lockheed Martin Aeronautics to qualify a replacement for the Cd. The primary fasteners in question are NAS 1580 and NAS 4452 fasteners. Four candidate coatings were selected for evaluation: electroless nickel (EN), electroless nickel composite (EN-PTFE), electrodeposited surface mineralization based zinc-nickel (Zn-Ni), and electroplated aluminum (Al). Stress corrosion, salt spray (fog) tests, torque-tension relationship, locking and breakaway torque measurements, and push-in and interference tests were used to evaluate alternatives to Cd coatings used for corrosion protection and lubricity on threaded parts. For comparison, Cd plated fasteners were tested at equivalent conditions as the controls.

Testing results showed that the surface mineralization based Zn-Ni coating best seems to mimic the overall characteristics of fasteners coated with cadmium. However, no one coating appears to offer the same broad range of properties as Cd plating. Salt spray tests indicated that EN and EN-PTFE exhibited red rust after 96 hours exposure. However**,** EN-PTFE demonstrated the best coefficient of friction feature, having the least overall torque to achieve the required tension. During torque tension tests, Zn-Ni performed nearly as well as Cd plating. Locking and break-away tests showed that Zn-Ni, EN-PTFE, and Cd nut/bolt sets meet the specification requirements. Al, Zn-Ni, and Cd showed acceptable resistance to stress corrosion up to 400 hours. However, only Al passed the 587 hours consistent load stress corrosion tests. Push–in tests revealed Cd plating required the minimum load to insert fasteners into aluminum structure with interference, followed by Zn-Ni. Furthermore, cross-sectional metallurgical examinations and interference tests were conducted to evaluate coating characteristics and adhesion strength between substrate and coating.

INTRODUCTION

Cadmium (Cd) plating is widely used on aircraft for the corrosion protection of airframe components and alloy steel fasteners [1-3]. The advantages of Cd plating are well known and are outlined in Table 1. In general, Cd plating offers good corrosion resistance, lubricity, solderability, adhesion, and ductility, as well as consistent torque-tension and uniform thickness on components with complex geometries. The main disadvantages associated with Cd plating are the high toxicity of Cd metal and its compounds. Because of the poisonous nature of Cd salts, the disposal of effluent from plating operations is subject to stringent controls, and the level of Cd that may be discharged into the environment is extremely low. For example, under European regulations, the use of Cd plating for general engineering purposes is no longer permitted. For these reasons, environmentally and technically viable alternatives are needed to replace cadmium coatings in aerospace applications.

Currently, various Cd replacement teams/programs such as the Joint Group on Pollution Prevention (JG-PP)/Boeing, the Joint Cadmium Alternatives Team (JCAT), the Canadian Cadmium Replacement Program (CCRP), and the REFOCUS Program (AEA Technology, European) have been investigating alternatives to Cd plating. A range of commercially available and potential coatings currently being assessed by the aerospace industry are given in Table 2. Each of the listed options has its own particular characteristics [1-2]. In addition, most experiments have been conducted on aerospace structural panels or components. However, little comprehensive study of various Cd alternatives was performed on threaded fasteners. Thus, there is a need to evaluate various alternative coatings for threaded fasteners. To this end, Lockheed Martin Aeronautics and Alcoa Fastening Systems have teamed to evaluate Cd alternatives for threaded fasteners used in the inlet of F-16 aircraft. One F-16 manufacturing process generates Cd dust from the fastener heads during sanding. The United States Air Force has funded Lockheed Martin Aeronautics to qualify a replacement for the Cd. The primary fasteners in question are NAS 1580 and NAS 4452 fasteners. Various Cd replacement technologies, including alternative substrates, were evaluated. A coating or plating can be completely avoided by the use of stainless steel or titanium in place of current Cd plated steels for the fastener substrate. However, the high cost of the alternative substrates, as well as weight (stainless steel) and strength (titanium) issues, made an alternative coating over alloy steel a more preferable option. In this investigation, four potential alternatives were selected for this evaluation.

- Electroless nickel (EN),
- Electroless nickel composite (EN-PTFE),
- Electrodeposited surface mineralization based zinc-nickel (Zn-Ni),
- Electroplated aluminum (Al).

Ideally, the Cd alternative has four major engineering jobs to do [2], often doing them simultaneously: (1) providing lubrication and consistent friction control for fasteners, (2) providing corrosion protection for substrate alloy steel, (3) acting as a barrier coating base, and (4) providing galvanic protection or compatibility with aluminum joint structures. Thus, based on these four major Cd application characteristics, comprehensive studies of Cd alternatives on threaded fasteners were performed. Detailed, carefully controlled experiments and microscopy studies were used to evaluate alternatives to Cd coatings used for corrosion protection and lubricity on threaded parts, including stress corrosion, salt spray (fog) tests, torque-tension relationship, locking and breakaway torque measurements, and push-in and interference tests. All testing was designed to simulate the typical use of threaded fasteners. For comparison, Cd plated fasteners were tested at equivalent conditions as the controls.

EXPERIMENTAL PROCEDURES

1. Fasteners

The scope of this project was limited to applications on substrates of low strength steel alloy (less than 200 ksi) threaded parts. The alloy steel 8740 fasteners with part number NAS1580A3T12 and diameter of 0.190 inch were provided by AFS Aichach (Robert-Bosch Street, 86551 Aichach, Germany). The purchased NAS1580A3T12 fasteners were Cd plated per specification AMS-QQ-P-416 Type II and followed by chromate conversion coating. To eliminate possible fasteners lot variations and to expedite investigation, all fasteners were purchased from the same lot, followed by random splitting. These were then stripped of the Cd plating and sent out for the application of the Cd alternative coatings. Around 80 pieces were retained for the controls.

2. Various Cd alternative coatings

In this investigation, four candidate coatings: Electrodeposited Zinc-Nickel (Zn-Ni), Electroplated Aluminum (Al), Electroless Nickel (EN), and Electroless Nickel composite (EN-PTFE) were chosen. Brief descriptions of all four coating alternatives are listed below. The surface mineralization based electrodeposited Zn-Ni plating is a three-part process. First, alkaline zinc-nickel plating was applied to the 8740 alloy steel. Then, the plated top layer was electrochemically converted into a zinc silicate layer. Finally, an organic sealer was applied as a topcoat for cosmetic appearance [11-12]. The organic bath aluminum electroplate process utilizes an organic solvent based water-free electrolyte to electroplate high purity thin amorphous and porous free aluminum onto various conductive substrates [9]. The Al was applied by individually racking the fasteners, followed by chromate conversion coating and lubrication. The EN deposition process is a controlled infusion of P-Ni plating based on a redox reaction in which the reducing agent is oxidized and Ni^{2+} ions are reduced on the substrate surface [13]. After EN deposition, no subsequent heat treatment was conducted. The EN-polytetrafluoroethylene (EN-PTFE) composite plating process deposits a durable, uniform, and dry lubricating coating that combines the low coefficient of friction PTFE (20-26%) in a strong, hard matrix of electroless Ni-P [14]. Similar to EN, no additional heat treatment was applied after plating. Table 3 lists specifications for each of the candidate coatings.

3. Engineering and Performance Test Requirements

Table 4 lists the critical engineering and testing requirements for evaluating alternatives to Cd coatings used for corrosion protection and lubricity on threaded parts. In addition to the listed short term 96 hours salt spray test, a long term salt spray test is in progress. The test will be continued until corrosion protection capabilities among all coatings can be identified. The listings also include acceptance criteria and references used for developing the tests. These evaluation tests were attempted to simulate the actual applications of threaded fasteners. Each test consisted of ten specimens for each of the selected candidate coatings, EN, EN-PTFE, Zn-Ni and Al. For comparison, Cd plated fasteners were tested at equivalent conditions as controls. It should be noted that the insertion tests were performed by pushing fasteners into well defined interference holes. The required load or installation force and fastener surface coating integrity were examined. The tests were monitored and recorded by a calibrated Digital Nicolet Oscilloscope Pro 40 model.

After receiving coated parts, each of the fasteners was examined for the quality attributes of appearance, coverage, and plating thickness. Cross-sectional optical microscopy was performed using a Nikon optical microscope (Model EPIPHOT 200, Japan). A portion of each sectioned specimen was mounted in diallyl phthalate powder (LECO Corporation, MI). The specimens then were mechanically polished to a 0.05 μm (alumina powder) surface finish using standard metallographic polishing techniques. During the evaluations, all testing machines and load cells were calibrated.

EXPERIMENTAL RESULTS

1. Appearance

The appearance characteristics of each of the plating technologies were acceptable. Representative coated fasteners of each plating type are shown in Figure 1. Coating is continuous, uniform in appearance, and free from contaminants and other apparent defects.

2. Thickness

A compilation of thickness measurements is shown in Figure 2. On threaded parts the desired thickness was 0.0003 inch, although the upper and lower limits are not specified. The thickness is measured by two approaches, cross-sectional examinations and diameter measurements before and after coating stripping. The average thickness of 0.0005-0.0006 inch for EN, EN-PTFE and Al were observed to be significantly greater than desired. However, Cd plating thickness of around 0.0001 inch was lower than specification requirements. The surface mineralization based Zn-Ni had an average thickness of 0.0003 inch, which met the desired thickness. The influence of coating thickness on the test results is discussed in the individual test sections below.

3. Salt Spray (Fog) Corrosion Resistance

Representative candidate images of 96 hours exposure to neutral salt spray are shown in Figure 3. None of the Cd, Zn-Ni, and Al fasteners showed any evidence of red rust. The Cd plating performed very well, with no significant color change. The Al performed well, but the surface appearance did start to change from a light chromate conversion coating color to a metallic white. It appeared that the Al samples could have had a much stronger conversion coating applied. The Zn-Ni fasteners showed white splotches, possibly due to inappropriate use of the black sealer, which could result in the early appearance of white spots [15]. However, it was reported that Zn-Ni plating could have light white corrosion products during early exposure to salt fog. The appearance of the Zn-Ni samples changed little for the rest of exposure period [16]. The overall surface remained uniform without evidence of selective attack or pitting.

The EN and EN-PTFE coated fasteners proved to be less durable during salt fog, with red rust appearing very quickly. The corrosion may occur for the following reasons: (1) Thickness. The EN and EN-PTFE samples demonstrated thickness of 0.0005-0.0007 inch. In general, better corrosion resistance can be achieved with electroless Ni by applying thicknesses of 0.001 inch and more [1, 6 & 17]. (2) Pre and post heat treatment. Corrosion properties can be affected by the proper pre and post heat treatments. However, most results are contradictory. For example, Endon [17] reported post heat treatment gave a reduction in corrosion resistance for both EN and EN-PTFE. However, Huang [13-14] reported enhanced corrosion resistance due to improved coating density and structure. There is no specification about pre and post coating treatment. The authors attempted to apply additional chromate conversion coating on EN and EN-PTFE fasteners to improve salt spray corrosion resistance, but without success. (3) Coating porosity [18].

4. Lubricity

4.1 Locking and Breakaway Torque

During the lubricity evaluations, KFN541L-3F K-fast locking nuts with dry film lubrication were installed on the candidate fasteners. Based on specification NASM 2527 (for the first installation cycle), maximum locking torque is defined as the highest reading measured during the third complete turn of the nut after the top of the nut is flush with the end of the bolt. The break away torque is the torque required to start the nut rotation from its installed position during the removal cycle with no load on the base of the nut [19]. The requirements for these nuts are a maximum of 18 in-pounds torque during locking and a minimum of 2 in-pounds torque to start the nut rotating for removal. No axial load is allowed during the locking and breakaway testing. Nuts were engaged on the bolt threads and then driven an appropriate number of turns to expose 1 to 2 threads beyond the nut. The nut driving direction was reversed and torque was measured as the nut was driven off the bolt. Torque versus rotation curves for each Cd alternatives are shown in Figure 4.

The Cd, Zn-Ni, and EN-PTFE nut/bolt sets met the specification requirements (Figure 5). The measured locking torque is less than 18 inch-pounds. The breakaway torque mirrors the locking torque and in all cases is greater than 2 inch pounds. However, EN and Al run on (locking?) torques were generally higher, with at least one sample of each showing a locking torque of over 20 in-pounds (Figure 5).

In Figure 4, the curves for all 10 parts are shown overlaid. The locking feature of the nut is deformed during the locking process. Also, the dry film lubricant on the nut and the plating on the bolt become displaced and compressed. The curves for the cadmium plated nut/bolt samples show more consistent behavior than others (Figures 4 and 5). The greater spread in the torque values for the candidate coatings may indicate that the candidates have a higher variation of lubricity than cadmium. In addition, all coatings demonstrated a plateau in torque versus rotation curves, showing a constant torque value. In general, this occurs once the locking crimp on the nut engages the bolt threads. This is due to dimensional changes when the plating metal is pushed ahead of the locking crimp on the nut to produce a somewhat conical shape to the threads on the bolt.

4.2 Torque tension and coefficient of friction

The tension load as a result of a given nut torque was determined using torque-tension stationary equipment. Aerospace KFN541L-3F nuts with dry film lubrication were used. A 2400 lbf preload was used which is 75% of the required minimum ultimate tensile load of 3180 lbf. A linear relationship between torque and the resulting preload were achieved. Figure 6 shows the torque-tension results for all candidates. The curves shown are averages of 10 bolts per coating. In addition, torque-tension load data was collected for calculation of coefficient of friction. The calculated coefficient of friction distribution is shown on a frequency histogram in Figure 7. In general, it was desired that the candidate coatings demonstrate a low friction coefficient or mimic the torque-tension characteristics of bolts coated with Cd. An important point to note is that no supplemental lubrication was used on the fasteners tested here except Al. Lubricants such as cetyl alcohol could have a significant effect on torque-tension characteristics. It is expected that using an additional lubricant could make the alternative coatings more similar to Cd in torque-tension performance.

EN-PTFE was the best overall performer. It had the least overall torque to achieve the required tension and had the least variability from part to part (Figures 6 and 7). This was consistent with our expectations that EN-PTFE (NiP + PTFE) composite can provide great lubricity due to its self-lubricating and excellent anti-sticking characteristics [20].

Zn-Ni and Al coated bolts generally performed close to Cd with a similar torque necessary to achieve maximum tension (Figure 6). However, the frequency histogram revealed that Zn-Ni bolts had a smaller variability of coefficient of friction from part to part, slightly outperforming Cd and Al (Figure 7). The Al bolts demonstrated large variations in the coefficient of friction. In addition, three of the ten Al fasteners were unable to achieve the full maximum of 2400 lbf tension values. The required torque was so high that the torque wrench experienced slippage. This may relate to the Al rack plating application method, or to the need for additional lubrication. Al coatings applied by barrel plating are likely to show improvements in both overall properties and consistency from part to part.

EN was the worst performer of all candidates in torque tension. The EN coated fasteners were quite “stiff” and slow to develop tension at a set torque. The nuts were very tight and difficult to run onto the bolts. This may relate to overly thick plating. While the overall torque-tension values were lower than those for Cd (Figure 6), the EN fasteners had a high variation from part to part. In addition, the overall coefficients of friction were significantly higher than those for cadmium.

A micrograph of a Zn-Ni fastener taken after torque tension testing is shown in Figure 8. The tooth profile shows little or no wear. The coatings are partially removed from the bearing surfaces where load is applied.

5. Push-in and interference tests

The push in and interference tests were conducted by pushing candidate fasteners into predetermined interference aluminum holes at a constant rate of 4000 lbf/min (Figure 9(a)). Thus the required maximum load and load-displacement curves can be measured. The desired maximum installation load is less than 2000 lbs. In addition, fastener weight measurement and surface examination before and after insertion were conducted. One unforeseen issue with this test was that each Cd alternative had different plating thicknesses, while the aluminum holes had almost the same internal diameter, resulting in different diameter differences or interference levels between fastener and hole internal diameter (Figure 9(b)). This led to difficulties in data interpretation.

Cd was the best overall performer. Only one bolt was unable to achieve full push in until more than 2000 pounds of load were applied. It had the least overall load to push plated fasteners into the interference hole and had the least variability from part to part. In addition, weight measurements revealed that Cd had the minimum average weight change (Figure 10). This is likely due to the very thin coating thickness and the soft nature of Cd coating (Figure 9(c)). Al demonstrated the highest interference level among all coating alternatives. However, the overall push-in load is only slightly higher than 2000 pounds. This is likely due to the effect of supplemental lubrication. Zinc-nickel bolts performed nearly as well as Cd. While the overall push-in load values were higher than those for cadmium, the Zn-Ni fasteners had less than 2000 pounds of maximum push-in load. Further examination revealed little glazing and large weight loss after the insertion tests (Figure 10). This is possibly a result of the slightly thick plating and brittle nature of the silicate coating layer [11-12], resulting in the coating peeling off. The EN coated fasteners generally performed close to EN-PTFE and the overall loads were very high. This is likely due to the overly thick coating and good wear resistance of EN and EN-PTFE.

6. Stress corrosion testing

Resistance to stress corrosion cracking was evaluated per NASM1312-9 using passivated 304 austenite stainless steel fixtures. Ten fasteners for each coating system were tested. Each fastener was tightened with a KFN541L-3F nut. The bolts were tightened until the fastener tension load reached 2400 lbf, which is 75% of the fastener ultimate tensile strength. Each coating assembly was inspected periodically at 69, 109, 141, 230 and 587 hour intervals. After 587 hours of testing, stress corrosion resistance capabilities among all Cd alternatives could be identified, and the test was stopped. The fasteners were then thoroughly evaluated. Through the testing, evidences of white corrosion, red rust, and nut corrosion were noted. Candidate coatings were compared directly to the performance of cadmium; i.e. the appearance of red rust at an interval less than that for cadmium constitutes failure. The observation data for each coating group is included in Table 5. No fastener failures or cracks were identified. Photographs of each of the alternative coating systems at the end of 587 hours are shown below in Figure 11.

Both Al and Zn-Ni passed the test, with Al reaching 587 hours without any rust (Figure 11(b)). Mineral based Zn-Ni showed some light white corrosion product uniformly distributed on the surface (Figure 11(c)). This corrosion appeared after 231 hours of test and changed little during the remainder of the test. The Zn-Ni fastener assembly showed minor nut corrosion. However, no substrate red rust was identified (Figure 11(c)). Cd demonstrated significant red rust on the entire fastener (Figure 11(a)). In addition, EN and EN-PTFE coated fasteners showed voluminous red rust corrosion (Figures 11(d) and (e)). Thus, based on these observations, the ranking of various coating technologies could be categorized from the best to the worst as: Al, Zn-Ni, Cd, EN-PTFE, and EN.

The difference in nut corrosion between Zn-Ni and Al fasteners might be attributed to different galvanic electrochemical potential. In general, the larger potential difference between the galvanic pair, the more galvanic protection for the cathode metal [21]. Austenite stainless steel tends to corrode in high chloride environments, such as those employed in this test method. The difference in the degree of “red rust” can be treated as a qualitative measure of the ability of the three candidate materials to galvanically protect the austenite stainless steel nut. In the case of nickel, the relative corrosion potentials of nickel and austenite stainless steel are close enough together that there is minimal galvanic protection provided (Table 6). However, in the case of aluminum, the difference in corrosion potentials is quite large; hence, the aluminum coating is corroding preferentially to the austenite stainless steel, thereby galvanically protecting the austenite stainless steel. For the Zn-Ni, the zinc content is apparently sufficient to lower the corrosion potential relative to pure nickel. Thus, there is a moderate difference in the corrosion potentials between the Zn-Ni and the austenite stainless steel, leading to moderate level of red rust on nuts.

7. Experimental summaries

Table 7 shows a summary of the testing results for the Cd alternative candidates. It appears that no one coating offers the same broad range of properties as Cd plating. However, for the current investigation, Zn-Ni came closest to the Cd characteristics overall. Al was the superior coating in regards to corrosion protection testing, but faltered in the testing areas that required lubricity.

DISCUSSION AND FUTURE DEVELOPMENT

Over many decades, the use of Cd plating has become firmly concentrated in aerospace and automobile industries where metal finishing plays a significant role. Its limitations are well known and understood by engineers and designers. Many potential Cd replacement technologies have been identified, with knowledge of their behaviors gradually accumulating. The current evaluation focused on four representative Cd alternatives for threaded fasteners applications. It indicated that the surface mineralization based Zn-Ni plating best mimicked the various characteristics of bolts coated with Cd. However, a few other important issues need to be addressed. Therefore, it is of interest to investigate the various plating properties using previous studies of the various Cd alternatives, especially Zn-Ni and Al coating, and known metallurgy principles. The thickness effect is discussed first, next galvanic compatibility with aluminum alloys, then frictional properties, and finally future development.

1. Thickness

Although current experiments indicated that Zn-Ni and Al demonstrated better stress corrosion resistance than Cd plated fasteners, these three coatings had different thicknesses. The average Cd, Zn-Ni, and Al plating thickness was 0.0001, 0.0003 and 0.0006 inch thickness, respectively (Figure 2). Numerous studies reveal that overall corrosion resistance, including barrier and sacrificial properties, has a linear proportional relationship with coating thickness. For example, neutral salt fog tests based on ASTM B117 showed that the time taken for red rust to appear on alloy steel was around

1700 hours for a coating thickness of 5 μm, while doubling the coating thickness could lead to more than 3500 hours before red rust would appear [1]. It is reasonable to believe that more consistent coating thicknesses between the candidates could have affected the stress corrosion rankings. However, the Al coating has outperformed Cd in previous stress corrosion studies [22].

2. Galvanic compatibility with aluminum alloys

When a galvanic corrosion cell is created, the most active (anode) of the two materials is eroded and deposited on the least active (cathode). Galvanic corrosion could occur between any different contacting metals. It is preferable that the fastener be the cathode and the structural material it is inserted in be the anode.

So, if coated fasteners were inserted into common aluminum components, it is preferred that aluminum alloys be corroded and the fastener coating be protected. Cadmium is cathodic to all aluminum alloys, which is another attractive characteristic for its use in the aerospace application. Clearly, pure or 1xxx aluminum alloys could provide sacrificial protection to the substrate steel fastener. However, 1xxx aluminum alloys are anodic to the 2xxx and 7xxx series aluminum alloys used for aero-structure (Table 6). Therefore, pure or 1xxx aluminum coated fasteners would be preferentially attacked if in contact with 2xxx or 7xxx series aluminum alloys. Due to small anode vs. large cathode area scenarios, it is possible that this would result in accelerated depletion of the aluminum coating [21]. However, this would be highly dependent on the difference in potential between pure aluminum and the aluminum alloys. Further investigation would be necessary to quantify this characteristic.

For regular Zn-Ni plating, the issue is more complicated. A reversal in the direction of corrosion current flow has been shown to occur due to dezincification of the Zn alloys, leading to decreased galvanic corrosion driving force by ennobling the surface coating [1]. However, no data is available for the current surface mineralization based Zn-Ni plating. This could be a future development topic via tailoring composition. In general, the surface coating should be tailored to get an optimum position in the galvanic series, such that the coating is cathodic to the aluminum structure, yet sufficiently anodic to the 8740 to provide protection.

3. Friction coefficient

It is important that alternatives have good coefficients of friction for threaded fastener application since the large amount of torque used in tightening bolts is used for overcoming bolt/nut friction. Additional surface treatments such as chromate conversion treatment, and lubrication such as cetyl alcohol, could make the alternative coatings equal to Cd and the measured friction values largely *independent* of coating type. This is consistent with our experimental results. Current evaluation revealed a high friction coefficient with EN plated fasteners. This is partly due to a lack of surface treatment above the nickel layer. However, the additional sealer on Zn-Ni, and the chromate and lubrication on the Al coating significantly improved overall torque-tension characteristics. A high coefficient of friction of above 0.5 for pure aluminum coatings is not suitable for tribological properties critical applications [23]. Therefore, aluminum alloys coatings need post-deposition treatments such as chromating or top coating with lubricants.

4. Future development

To further the development of Cd alternatives, more careful control of coating thickness, surface treatment, and lubrication are needed. This could enable direct properties comparison of various plating technologies. In addition, the measurement of the corrosion potentials of the fastener material, coatings, and joining alloys could be used to assess galvanic compatibility of the entire material system. Also, continued investigations on secondary lubrication of these candidates could significantly improve their torquing and friction characteristics. Finally, stress and strength testing needs to be conducted to ensure that the performances of the as-coated fasteners have not been detrimentally affected.

CONCLUSIONS

This project was intended to evaluate a coating process that can be used for corrosion protection and lubricity on threaded fasteners as a replacement for Cd plating. Four candidate coatings were selected for evaluation: EN, EN-PTFE, surface mineralization based Zn-Ni, and Al. A series of evaluation tests were used to evaluate alternatives to Cd coatings, such as stress corrosion, salt spray test, torque-tension, locking and breakaway torque measurements, and push-in and interference tests. Testing results showed that the surface mineralization based Zn-Ni coating best seemed to mimic the overall characteristics of fasteners coated with cadmium. However, no one coating appears to offer the same broad range of properties as Cd plating. Furthermore, it is hard to conduct direct comparisons with different coating thicknesses, surface treatments, and lubrication among various Cd alternatives. Further evaluation would have more careful control of these parameters. It is expected that the results of this investigation could be applicable to a broad range of threaded fasteners used in the aerospace industry.

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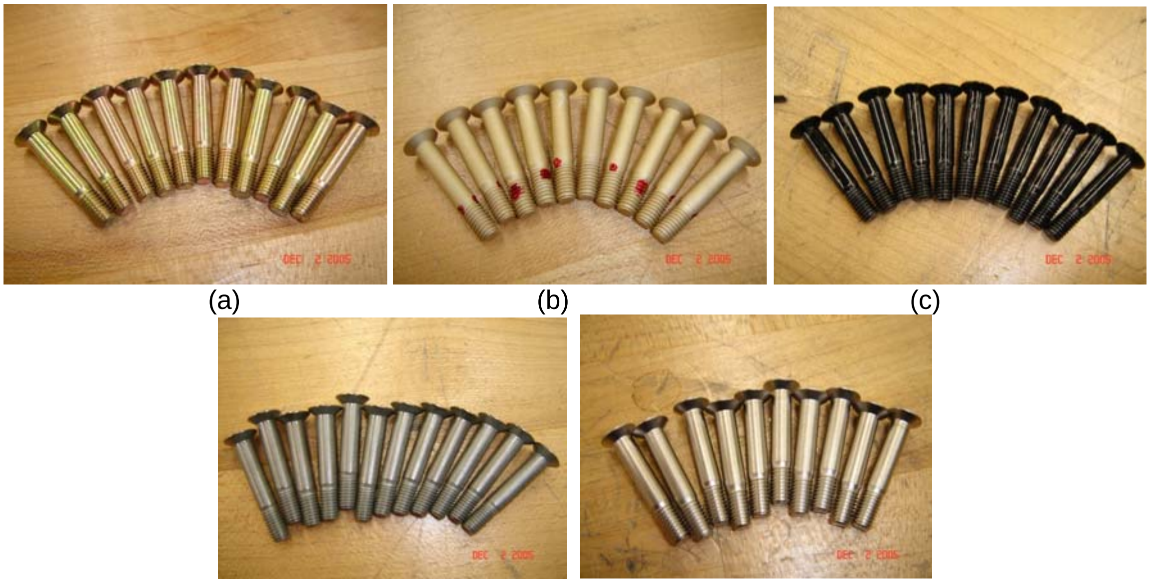

(a) (b) (c)

(d) (e)

Figure 1. Appearance as-plated (a) Cd, (b) Al, (c) Zn-Ni, (d) EN-PTFE and (e) EN fasteners.

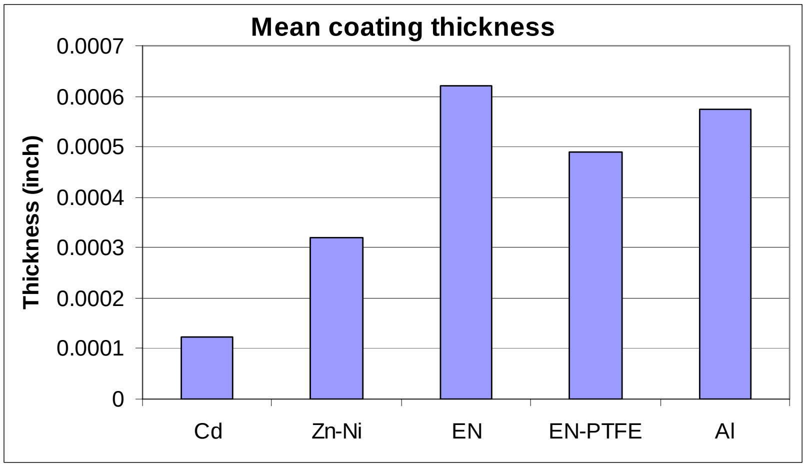
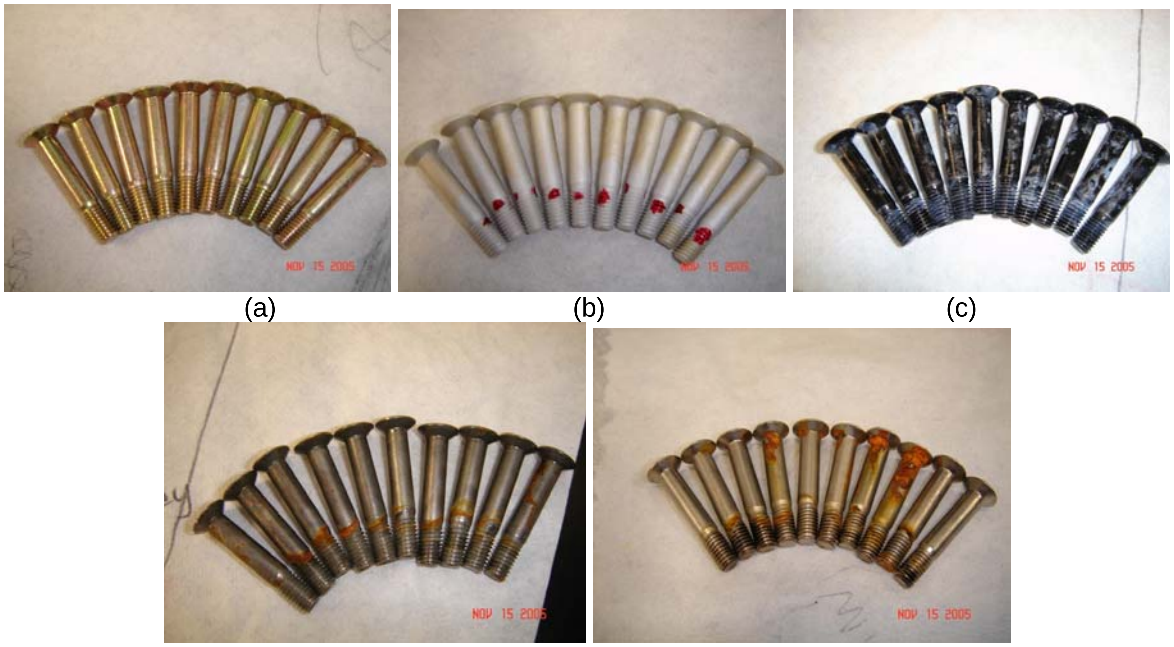


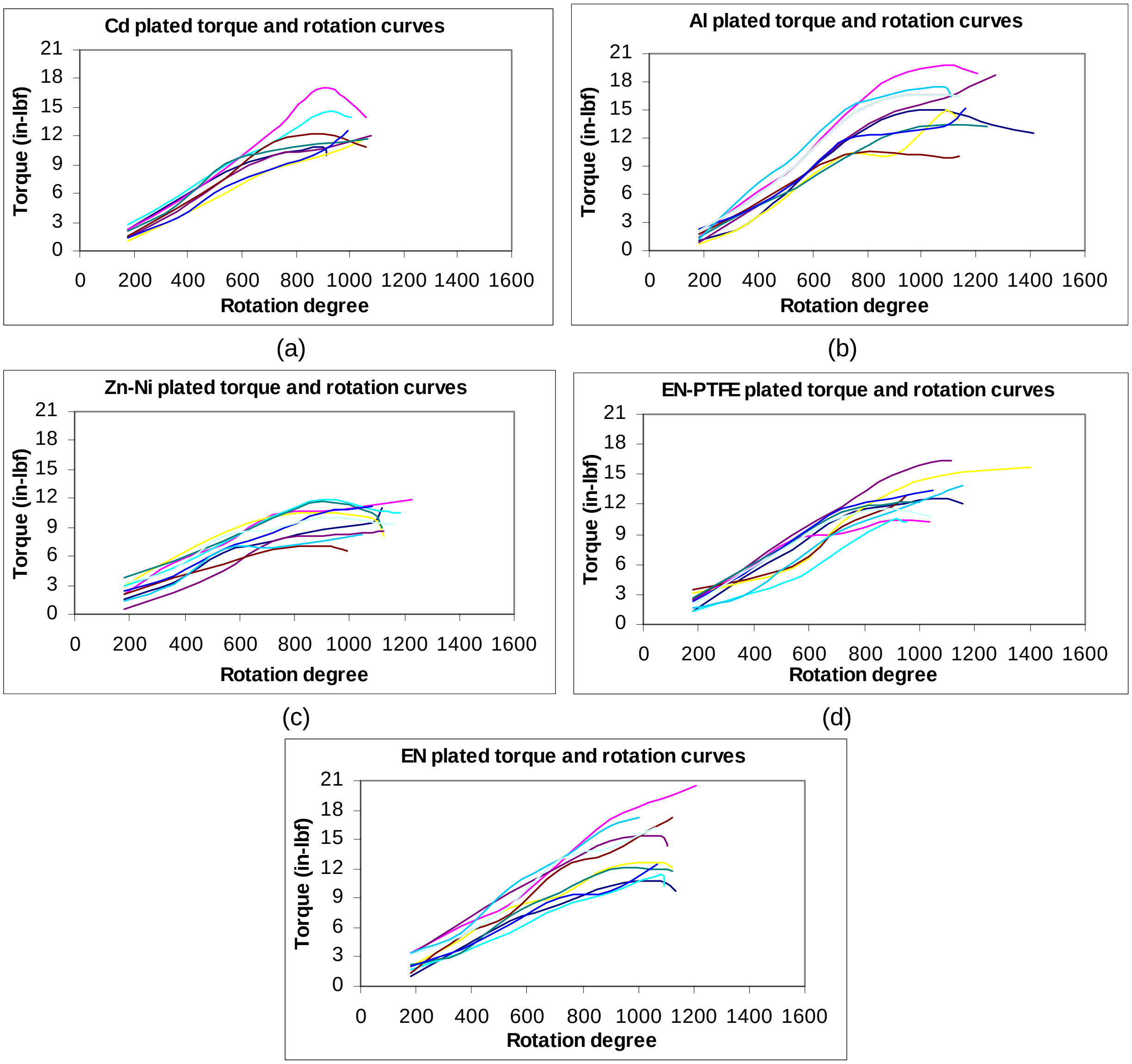
Figure 2. Summary of mean thickness of each Cd alternatives.



(a) (b) (c)

(d) (e)

Figure 3. Appearance of (a) Cd, (b) Al, (c) Zn-Ni, (d) EN-PTFE and (e) EN fasteners after 96 Hours Salt Spray .



Cd plated torque and rotation curves

Al plated torque and rotation curves

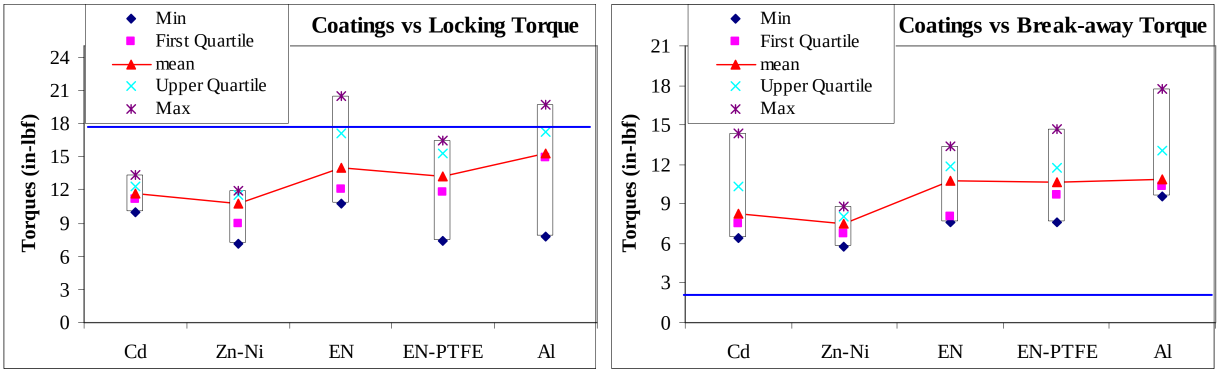
Zn-Ni plated torque and rotation curves

EN-PTFE plated torque and rotation curves

EN plated torque and rotation curves

(a) (b) (c) (d) (e)

Figure 4. Torque vs. rotation curves.



(a) (b)

Figure 5. Measured locking (a) and break-away torque of candidates coating fasteners. The horizontal lines show 18 in-pound maximum locking torque and a minimum 2 in-pound break away torque.

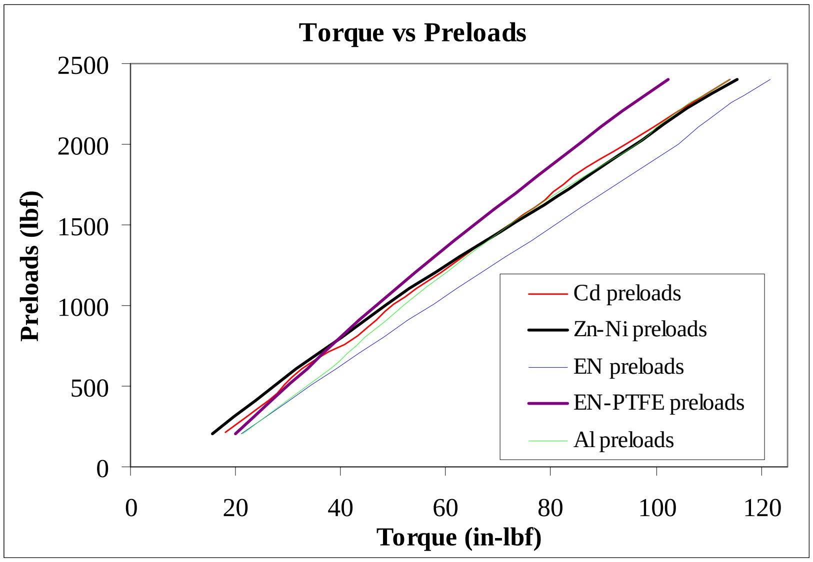
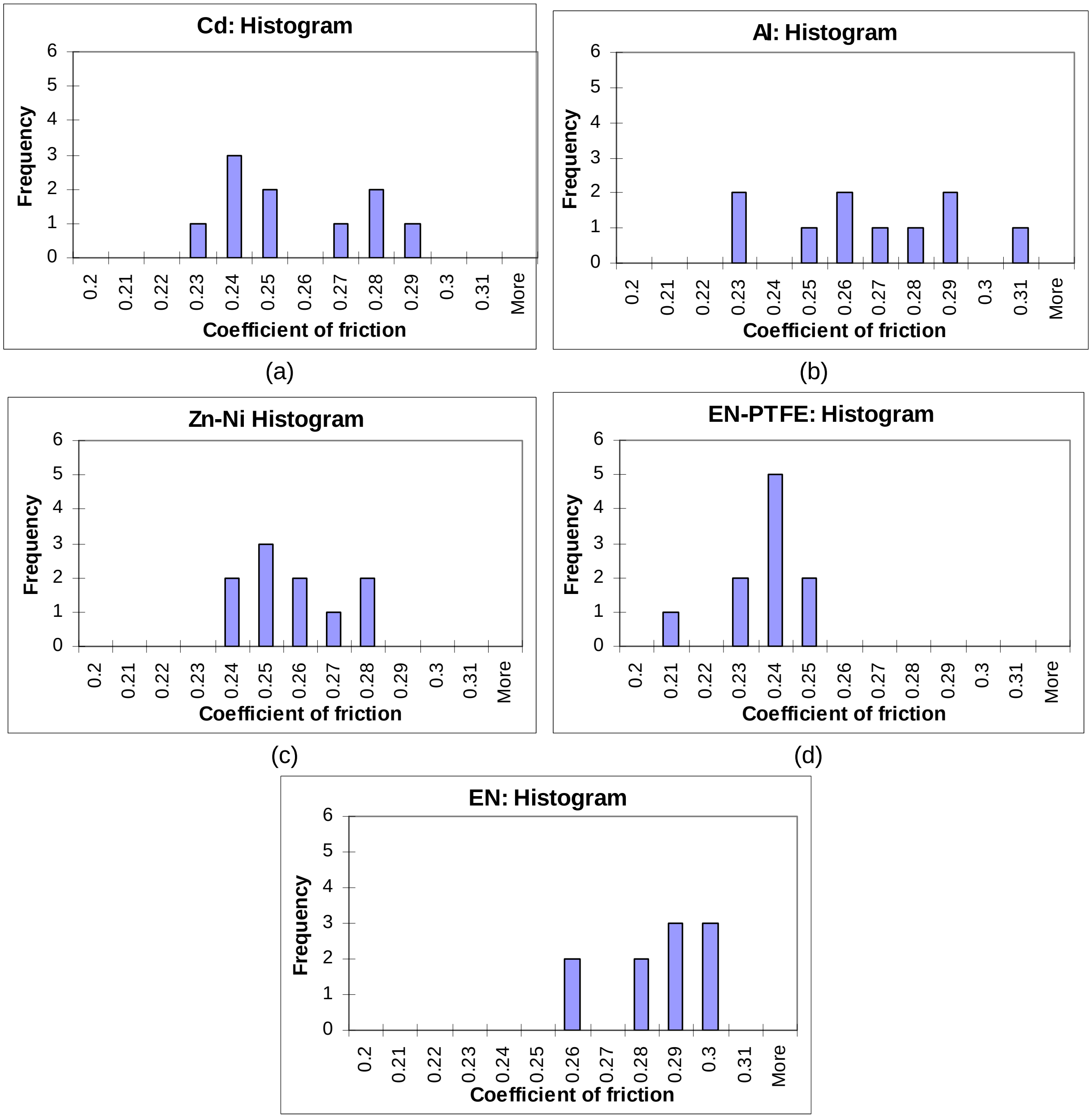


Figure 6. Torque-tension curves for various Cd alternatives with averages of 10 bolts per coating. It is indicated that EN-PTFE was the best overall performer, having the least friction and the least variability. In addition, Zn-Ni slightly outperformed Cd.



(a) (b) (c) (d) (e)

Figure 7. Frequency histogram of coefficients of friction.

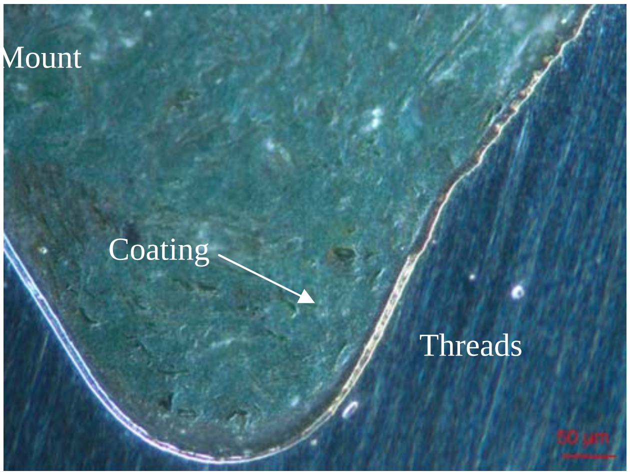
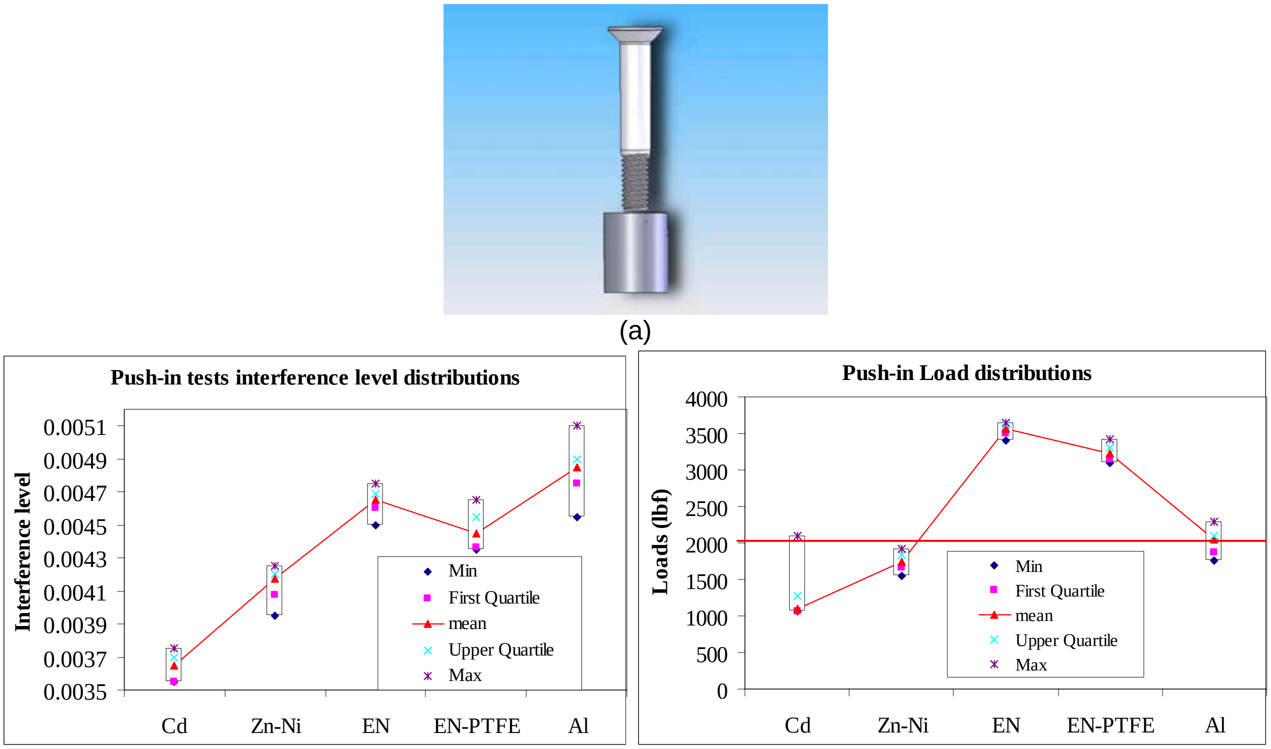


Figure 8. Micrograph of Zn-Ni plating fastener thread profile after torque-tension evaluation.



(a)

(b)

(c)

Figure 9. Schematic representation of push-in and interference test set up (a), and different interference level between fastener and hole internal diameter (b), and measured maximum installation loads (c).

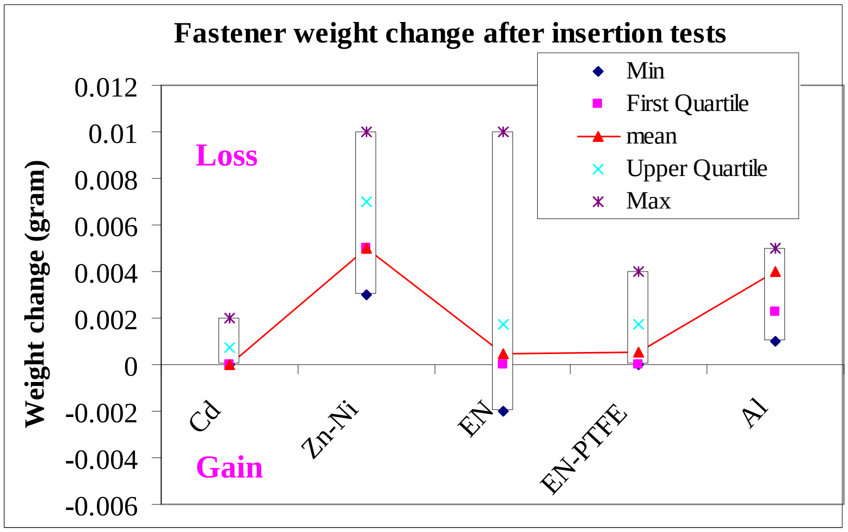
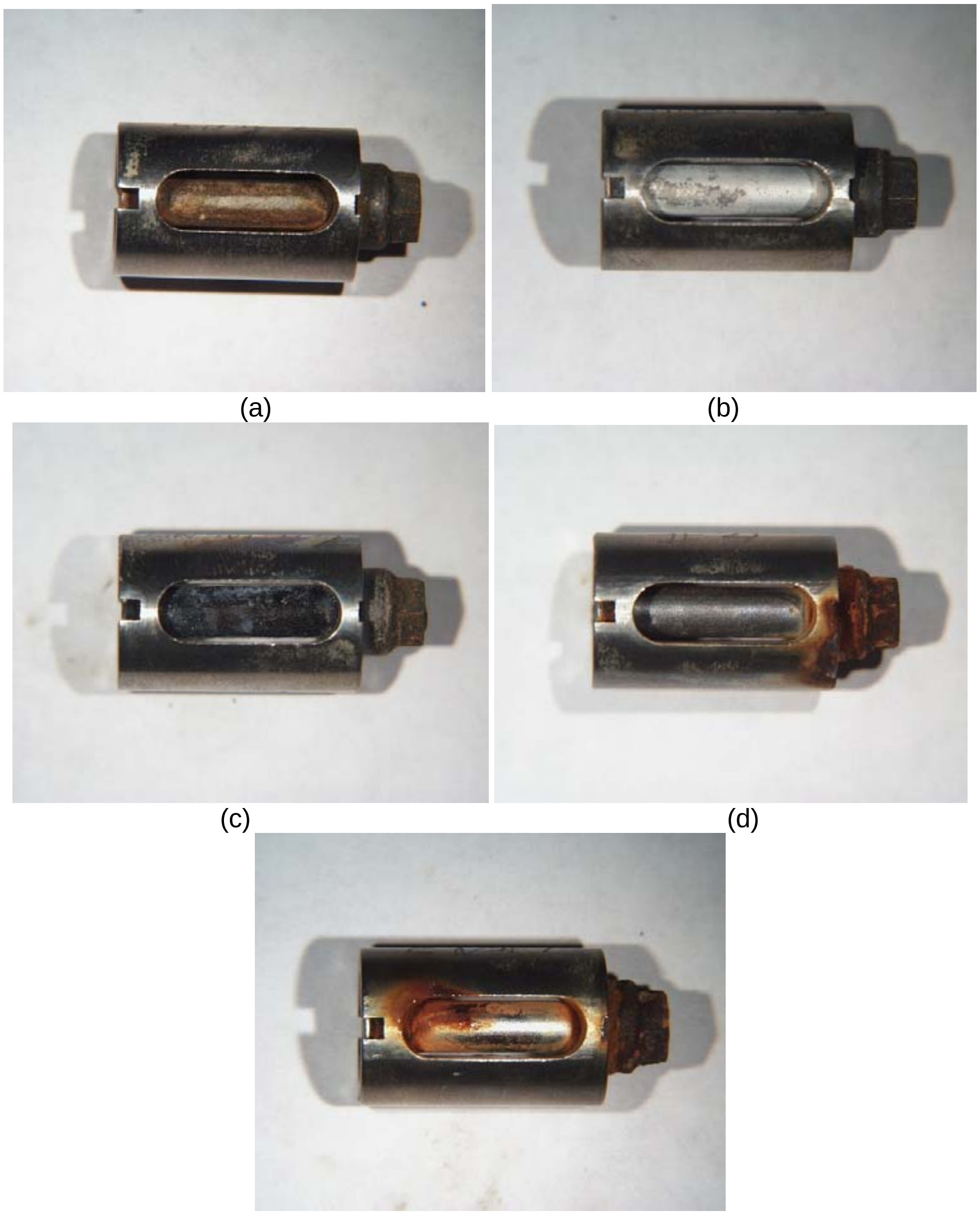


Figure 10. The measured weight change before and after insertion tests.



(a) (b) (c) (d) (e)

Figure 11. Representative and overall appearance of (a) Cd, (b) Al, (c) Zn-Ni, (d) EN-PTFE and (e) EN plated fasteners after 587 hours of stress corrosion testing.

Advantages	**Disadvantages**
Good barrier against corrosion	Toxicity
Sacrificial corrosion protection	Regulatory burden
Galvanic compatibility with aluminum structure	Embrittlement of steel
Good surface lubricity	Embrittlement of Titanium alloy
In-situ repair by brush-plating	Hydrogen embrittlement associated with plating process

Table 1. Advantages and Disadvantages of Cd plating [1-3].

Coating type	Coating Materials	Comments
Aqueous electroplates	Sn-Zn, Zn-Ni, Ni, Ni-PTFE	Under extensive evaluation in the aerospace industry [4-6]
Chemical Vapor deposition	Al and alloys	Not commercially available, under development [7-8]
Organic bath electroplates	Al	Only one commercial process in the U.S. [9]
Molten salt bath electroplate	Al-Mn	Not commercially available, under development [10].
Ion vapor deposition (IVD) aluminum	Al	Vacuum deposition of Al. Wide Use in Aerospace
Metal-Filled composites	Al or Zn in ceramic or polymer	Metal/ceramic Material Used in Aircraft. Polymer/Al and Zn Used in Vehicle Bolts [3]

Table 2. Cadmium Replacement Technologies.

Coatings	Specification	Conversion coating	Target thickness (inch)	Lubrication
Cd	QQ-P-416 Type II Class 2	Chromate	0.0003	None
Zn-Ni	AMS 2417 Type II	Surface mineralization	0.0003	None
Aluminum	MIL-DTL-83488D Type II, Class 3	Chromate	0.0003	Wax based lubrication
EN	AMS-C-26074 Class 1	None	0.0003	None
EN-PTFE	AMS 2404C Class 1	None	0.0003	None

Table 3. Summary of Coating Information.

Engineering Requirement	Test Type	Reference Specification	Evaluation Criteria
Physical properties	Appearance	AMS-QQ-P-416	Coating is continuous, smooth, uniform in appearance, free from blisters, burning, contaminants, and other apparent defects.
Resistance to Stress Corrosion Cracking	Stress Corrosion	NASM1312-9	1. Evaluate based on the time to failure for the benchmark Cadmium-plated test fasteners. Determine if failure for fasteners with candidate coating is significantly different than equivalent Cadmium-plated fasteners. 2. Development of cracks or failure by fracture constitutes failure of the specimen.
Corrosion Protection	Salt Spray (Fog)	NASM1312-1 and ASTM B117-03	Minimum 96 hours exposure without any form of rust.
Coefficient of friction	Torque-Tension	NASM1312-15 NASM25027	Determine if Torque-tension relationship for fasteners with candidate coating is significantly different than Cadmium-plated fasteners. Determine if fasteners with candidate coating experiences any defects such as thread stripping or galling.
Vibration resistance	Locking and Breakaway Torque	NASM1312-31 NASM25027	1. During installation, the maximum locking torque shall not exceed max. requirement. During removal, the minimum breakaway torque is greater than min. requirement. 2. Evaluate the difference between fasteners with candidate coating and the equivalent Cadmium-plated fasteners.
Resistance to insertion	Push–in test		Evaluate force required to insert fasteners into Aluminum structure with interference.
Interference	Adhesion test	ASTM B 571-91	2. Fastener surface separation (weight loss, flaking, peeling, or blistering) for candidate coating is within the range for cadmium plated fasteners. 3. No separation (flaking, peeling, or blistering) from the basis metal or from any underplating at the edge.

Table 4. Critical Engineering and Performance Test Requirements for corrosion protection and lubricity on threaded parts NAS1580A3T12. Each test consists of 10 threaded fasteners in a total of 50 for each selected coating: EN and EN-PTFE, Zn-Ni and Al, in addition to Cd plating.

Group	69 hours visual	109 hours visual	141 hours visual	231 hours visual	587 hours visual
Cd	1	1, 7	1, 7	1, 7	1, 2, 3, 4, 5, 7
Al	1	1, 2, 8	1, 2, 8	1, 2, 8	1, 2, 8
Zn-Ni	8, 9	8, 9	8, 9	8, 9	7, 10
EN	4, 7	4, 6, 7	4, 6, 7	4, 6, 7	4, 6, 7
EN-PTFE	7	4, 6, 7	4, 6, 7	4, 6, 7	4, 6, 7
1: Plating discolored; 2: Plating pitted; 3: Plating disappeared; 4: Rust forming on fastener head; 5: Rust forming on fastener shank; 6: Rust forming on fastener threads; 7: Rust forming on K-nut; 8: No rust; 9: No discoloration; 10: White surface corrosion					

Table 5. The periodical examination results of stress corrosion test Cd alternatives.

Anodic	Magnesium
↑	Zinc
	Pure Aluminum
	Aluminum 5000 series
	Cadmium
	Aluminum 2000 series
	Aluminum 7000 series
	Alloy steel 8740
	Stainless steel (active)
	Nickel (active)
	Nickel (passive)
↓	Stainless steel (passive)
Cathodic	Graphite

Table 6. Excerpt of the galvanic electrochemical potential series of metals [1, 21].

Group	Salt-spray	Friction coefficient	Locking torque	Break-away torque	Push-in load	Stress-corrosion
Cd	Base	Base	Base	Base	Base	Base
Al	Pass	Fail	Fail	Pass	Fail	Excellent
Zn-Ni	Pass	Pass	Pass	Pass	Pass	Pass
EN-PTFE	Fail	Excellent	Pass	Pass	Fail	Fail
EN	Fail	Fail	Fail	Pass	Fail	Fail

Table 7. Summaries of current Cd evaluation. The Cd plating was treated as baseline for comparison.