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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION  
PATUXENT RIVER, MARYLAND



**TECHNICAL INFORMATION  
MEMORANDUM**

REPORT NO: NAWCADPAX/TIM-2016/189

**STRESS CORROSION-CRACKING AND CORROSION FATIGUE IMPACT  
OF IZ-C17+ ZINC-NICKEL ON 4340 STEEL**

by

**Craig Matzdorf  
Charles Lei  
Matt Stanley**

**17 May 2017**

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14. ABSTRACT Sacrificial metallic coatings like cadmium and aluminum are key protective materials for high-strength steels, corrosion-resistant steels and other cathodic materials used on aircraft. The effect of these coatings on the stress-corrosion cracking and corrosion fatigue performance of the base metals is critical to understand for intended applications.  Although it works well, cadmium is toxic and a carcinogen and alternatives have been sought which are similarly effective but have minimal environmental, safety, and health risks. Aluminum is effective, but is expensive to apply. The currently used application method at Navy Fleet Readiness Centers (FRCs), ion-vapor deposition (IVD), is line-of-sight limited, meaning not all parts that can be electroplated with cadmium can be effectively coated with IVD aluminum.  A new coating, a zinc-nickel alloy produced from a solution supplied by Dipsol, has shown promising performance for many coating requirements including general corrosion, adhesion, and flexibility. The stress-corrosion cracking and corrosion fatigue performance of this new coating was not known. In addition, the impact of corrosion-inhibiting primer and topcoat on these degradation mechanisms was not known.  This report documents the work completed to assess the stress-corrosion cracking and corrosion fatigue of the IZ-C17+ zinc-nickel coating with a trivalent chromium passivation (Dipsol IZ-264) on 4340 steel, a common high-strength steel test substrate. Funding was provided by the OSD Corrosion IPT project W12NA06.					
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## SUMMARY

Sacrificial metallic coatings like cadmium and aluminum are key protective materials for high-strength steels, corrosion-resistant steels and other cathodic materials used on aircraft. The effect of these coatings on the stress-corrosion cracking and corrosion fatigue performance of the base metals is critical to understand for intended applications.

Although it works well, cadmium is toxic and a carcinogen and alternatives have been sought which are similarly effective but have minimal environmental, safety, and health risks. Aluminum is effective, but is expensive to apply. The currently used application method at Navy Fleet Readiness Centers (FRCs), ion-vapor deposition (IVD), is line-of-sight limited, meaning not all parts that can be electroplated with cadmium can be effectively coated with IVD aluminum.

A new coating, a zinc-nickel alloy produced from a solution supplied by Dipsol, has shown promising performance for many coating requirements including general corrosion, adhesion, and flexibility. The stress-corrosion cracking and corrosion fatigue performance of this new coating was not known. In addition, the impact of corrosion-inhibiting primer and topcoat on these degradation mechanisms was not known.

This report documents the work completed to assess the stress-corrosion cracking and corrosion fatigue of the IZ-C17+ zinc-nickel coating with a trivalent chromium passivation (Dipsol IZ-264) on 4340 steel, a common high-strength steel test substrate. Funding was provided by the OSD Corrosion IPT project W12NA06.

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## INTRODUCTION

The protection of cathodic metallic materials used for aircraft components, like 4340, Aermet 100, and PH 13-8 corrosion-resistant steel, is critical to keep the steel from pitting and cracking due to exposure to the operating environment. Two important properties are resistance to stress-corrosion cracking (SCC) and corrosion fatigue. These are insidious failure mechanisms that can lead to part failure in service, an undesirable outcome.

## BACKGROUND

Cadmium and aluminum coatings are currently used to protect high-strength steels from corrosion, pitting, and cracking. These coatings are applied on new components and also at Navy Fleet Readiness Centers (FRC) during component repair and overhaul. Both are effective but each has shortcomings.

Cadmium is electroplated or sometimes applied in a vacuum chamber. The electroplating process allows for coating of all component surfaces using a low-cost method. Cadmium is toxic and carcinogenic and alternatives are desired to eliminate these risks.

Aluminum is electroplated or applied by the ion-vapor deposition (IVD) process. At Navy FRCs, the IVD process is used. This requires a vacuum and is limited by line-of-sight, so not all surfaces of components can be coated depending on their geometry. IVD is a relatively high-cost practice and requires more maintenance than a cadmium electroplating line.

Alternatives to cadmium have been investigated for at least 50 years, with IVD aluminum being an early commercialized alternative. More recently, zinc-nickel alloys have been optimized to have coating properties that are very close to cadmium. The deposition process for these new alloys is electroplating.

More specifically, Dipsol provides a commercial zinc-nickel plating solution, IZ-C17+, that has been optimized for use on high-strength steels to perform similarly to cadmium and aluminum. One shortcoming of the data available is the ability of the coating to minimize SCC and corrosion fatigue of the substrate material and how it compares to cadmium and aluminum. These are two critical requirements for sacrificial coatings used on Navy and Marine Corps aircraft components.

Prior work by Lee, et al [Reference 1] documents the method to assess SCC and corrosion fatigue and the performance of electroplated cadmium on 4340 steel by itself, with a MIL-PRF-23377 Class C primer, and with both the primer and a MIL-PRF-85285 gloss white topcoat. This protective coating system is typical for high-strength steel components.

PURPOSE

The purpose of this evaluation was to assess the ability of electroplated IZ-C17+ zinc-nickel to suppress SCC and corrosion fatigue of 4340 steel using methods previously developed by the Materials Engineering Division. The zinc-nickel coating was assessed by itself, primer only, and with the primer and standard gloss white topcoat used on fleet aircraft components. The primer used was a standard MIL-PRF-23377, TY I chromate-based primer currently used on high-strength steel parts that are coated with cadmium or aluminum.

Figures 1 and 2 show a part made from Hy-Tuf steel forging heat treated to 220 - 250 ksi that has been coated with IVD aluminum and then primed and topcoated using a MIL-PRF-23377 Class C primer and MIL-PRF-85285 gloss white topcoat, respectively.

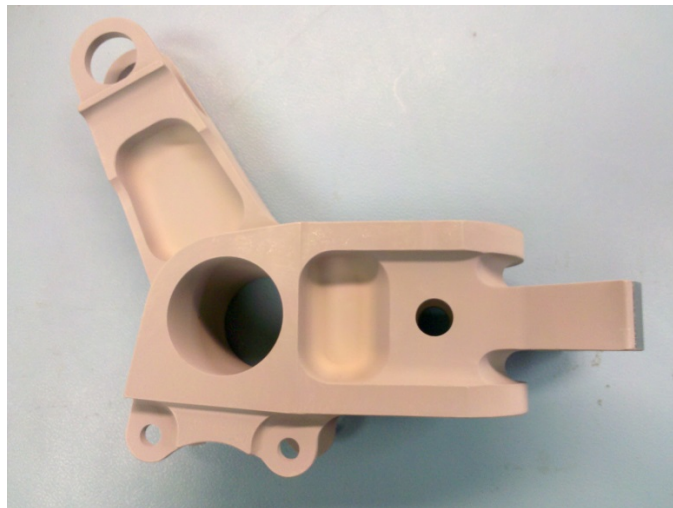


Figure 1. T-45 Pivot with IVD Aluminum Coating, Passivated with a Chromate Conversion Coating



Figure 2. T-45 Pivot with Full Protective Coating System

## METHODS

### MATERIAL AND SPECIMENS

As the base or substrate material of the specimens, 4340 steel plate was machined into round hourglass fatigue test specimens in L-orientation and square bar SCC test specimens in L-T orientation. Details for 4340 and specimen geometries are contained in Reference 1.

### COATINGS

The IZ-C17+ zinc-nickel coating and IZ-264 trivalent chromium passivation were applied at FRC-Southeast from a demonstration plating line. The MIL-PRF-23377 Class C primer and MIL-PRF-85285 Type I topcoat were also applied by FRC-Southeast artisans in their paint facility. The zinc-nickel was applied at 0.5 mils, the primer at approximately 1.0 mil, and the topcoat at approximately 2.0 mils.

### CORROSION FATIGUE TEST

A closed-loop servo-hydraulic mechanical test machine, MTS, of 20 kip capacity, was employed for the fatigue test. The fatigue test was carried out with hourglass specimens under tension-tension cyclic loading at stress ratio (R) of 0.1 and frequency 10 Hz in air and circulating aqueous 3.5% NaCl solution of pH 7.3.

### STRESS CORROSION CRACKING TEST

An accelerated SCC test was conducted in a rising step load (RSL) 1000 SI-Multi-Mode Test System. This system includes a bending frame, a tensile loading frame, an electrolyte reservoir, a pump for electrolyte circulation, a saturated calomel electrode, a platinum counter electrode, a computer, and a printer. The un-precracked coated specimens were step-loaded until the load dropped in four-point bending under constant displacement control, while held at a given



potential in aqueous 3.5% NaCl solution of pH 7.3. The load drop corresponded to the threshold stress intensity for stress corrosion cracking,  $K_{OSCC}$ , for the coated specimen.

### EXPERIMENTAL RESULTS

#### CORROSION FATIGUE TEST

Figure 3 shows the corrosion fatigue results for the uncoated 4340, IZ-C17+ zinc-nickel as-plated, IZ-C17+ zinc-nickel with primer, and IZ-C17+ zinc-nickel with the primer and topcoat. The figure shows that the zinc-nickel improves performance at stress levels below 220 ksi. The use of MIL-PRF-23377 Class C primer on the zinc-nickel does not affect the zinc-nickel performance. The MIL-PRF-85285 Type II gloss white topcoat appears potentially improves fatigue life at low stress levels but does not otherwise affect performance. This may be due to the flexibility of the topcoat which may extend the fatigue life by acting as a more effective barrier to the salt solution during testing.

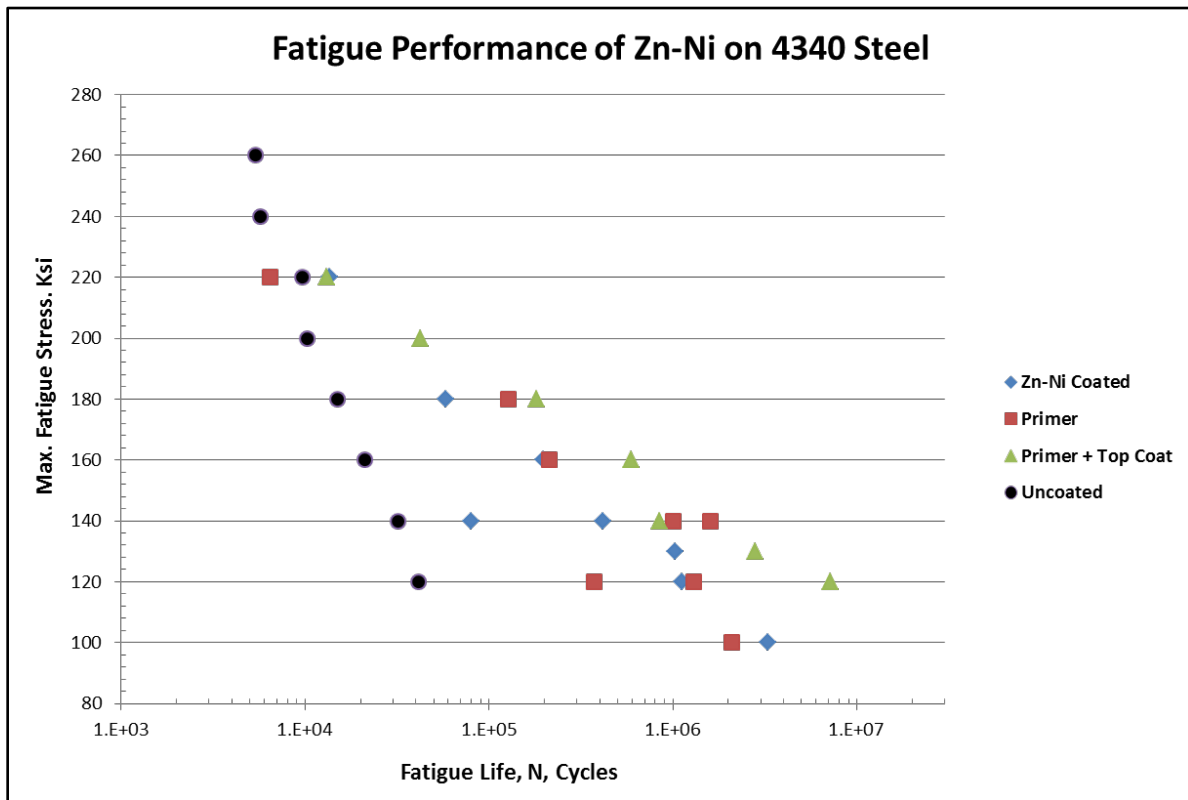


Figure 3. Corrosion Fatigue Performance of Zn-Ni on 4340 Steel

Figure 4 shows a comparison of the corrosion fatigue performance of IZ-C17+ zinc-nickel to cadmium on 4340 steel. The cadmium data is from prior work per Reference 1. The figure shows that the zinc-nickel may have a slightly lower corrosion fatigue life compared to cadmium, but like the data in Figure 3, the number of samples was limited, so a statistical assessment is not

possible. It's clear that both coatings provide a significant increase in life compared to uncoated 4340 (Figure 3).

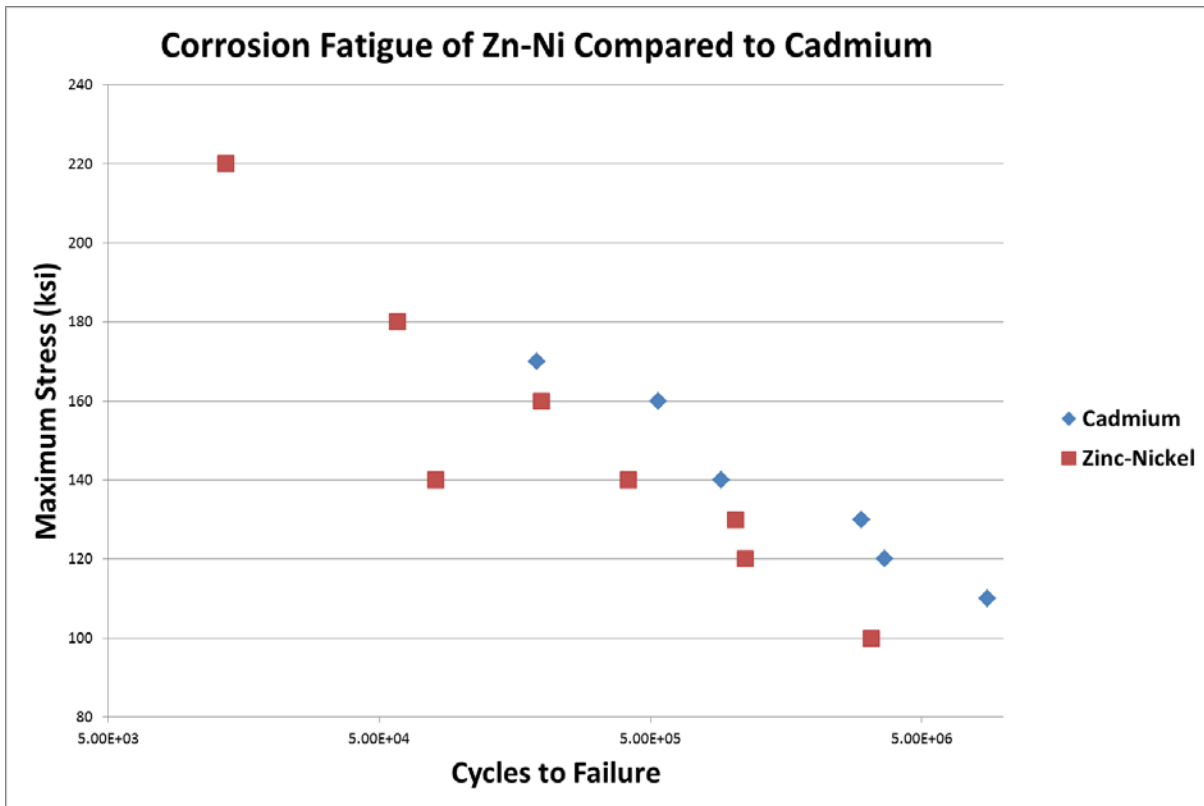


Figure 4. Corrosion Fatigue Performance of Zn-Ni Compared to Cadmium on 4340 Steel

Figure 5 shows a comparison of the corrosion fatigue performance of zinc-nickel to cadmium with MIL-PRF-23377 Class C primer and MIL-PRF-85285 Type I gloss white topcoat. The cadmium data is from prior work per Reference 1. The figure shows that the zinc-nickel and cadmium-based coating systems perform similarly. In addition, the organic coatings may improve the corrosion fatigue life compared to unpainted sacrificial coatings, especially at lower stress levels. These full coating systems, like the sacrificial coatings by themselves, provide a significant increase in corrosion fatigue life compared to the uncoated 4340 steel.

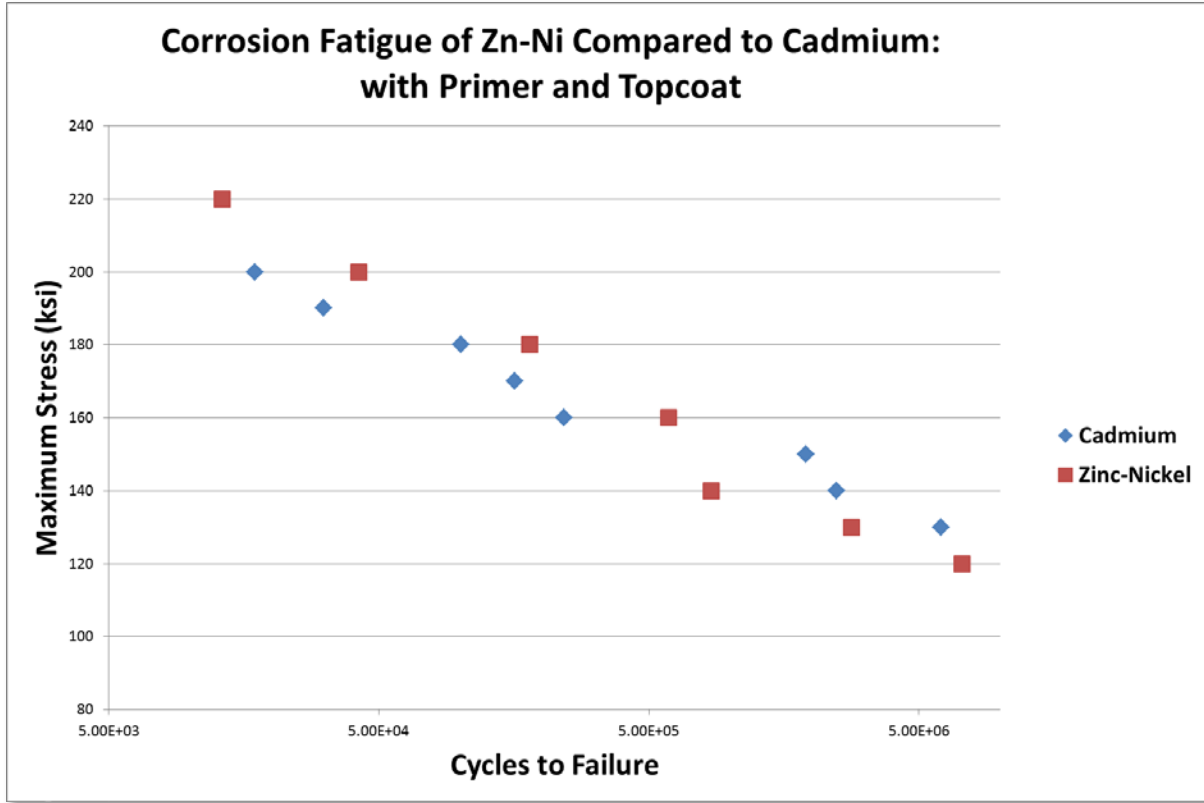


Figure 5. Corrosion Fatigue Performance of Zn-Ni Compared to Cadmium on 4340 Steel

Data from Reference 1 for performance of cadmium in air also suggest that improved protection may be achieved if primers and topcoats are optimized for corrosion fatigue performance and that a corrosion fatigue requirement may be relevant to the primer and topcoat material specifications. Currently, these types of products are developed and implemented without considering their effect on corrosion fatigue.

STRESS CORROSION CRACKING TEST

Figure 6 shows the SCC results for the IZ-C17+ zinc-nickel as-plated, IZ-C17+ zinc-nickel with primer, and IZ-C17+ zinc-nickel with primer and topcoat. The figure shows that the primer and topcoat each have a significant, additive, positive effect on SCC resistance independent of applied potential. The primer data point at -0.6 volts may be an anomaly, but was included for completeness.

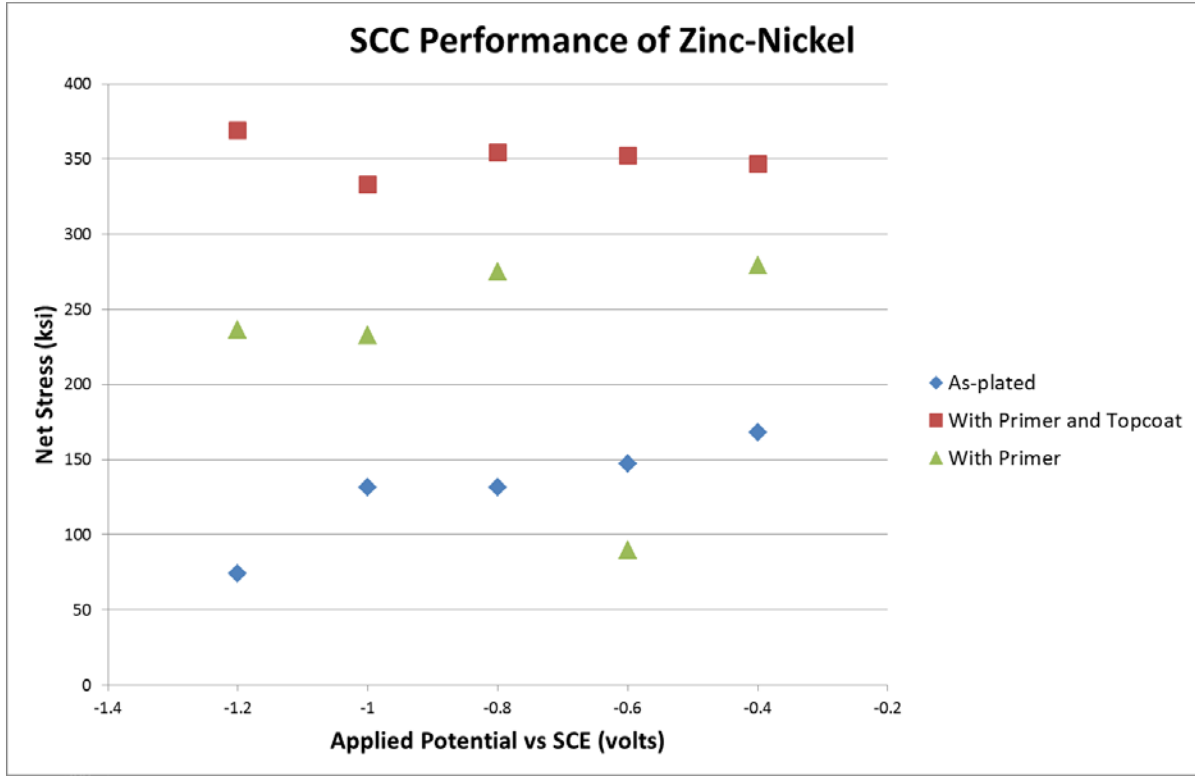


Figure 6. SCC Performance of Zn-Ni on 4340 Steel

This result is similar to cadmium as reported in Reference 1. This is a powerful justification for the use of the current coating protection scheme and correlates with the excellent in-service performance of components with these coatings. The data continue to suggest that, similar to corrosion fatigue, even better protection may be achieved if primers and topcoats are optimized for SCC performance and that an SCC requirement may be relevant to the primer and topcoat material specifications.

Figure 7 shows the SCC performance of zinc-nickel compared to cadmium without organic coatings. Cadmium data is from prior work per Reference 1. The figure shows that the zinc-nickel and cadmium provide similar SCC resistance at -0.8 to -1.2 volts. At higher voltages, the zinc-nickel provided better SCC resistance.

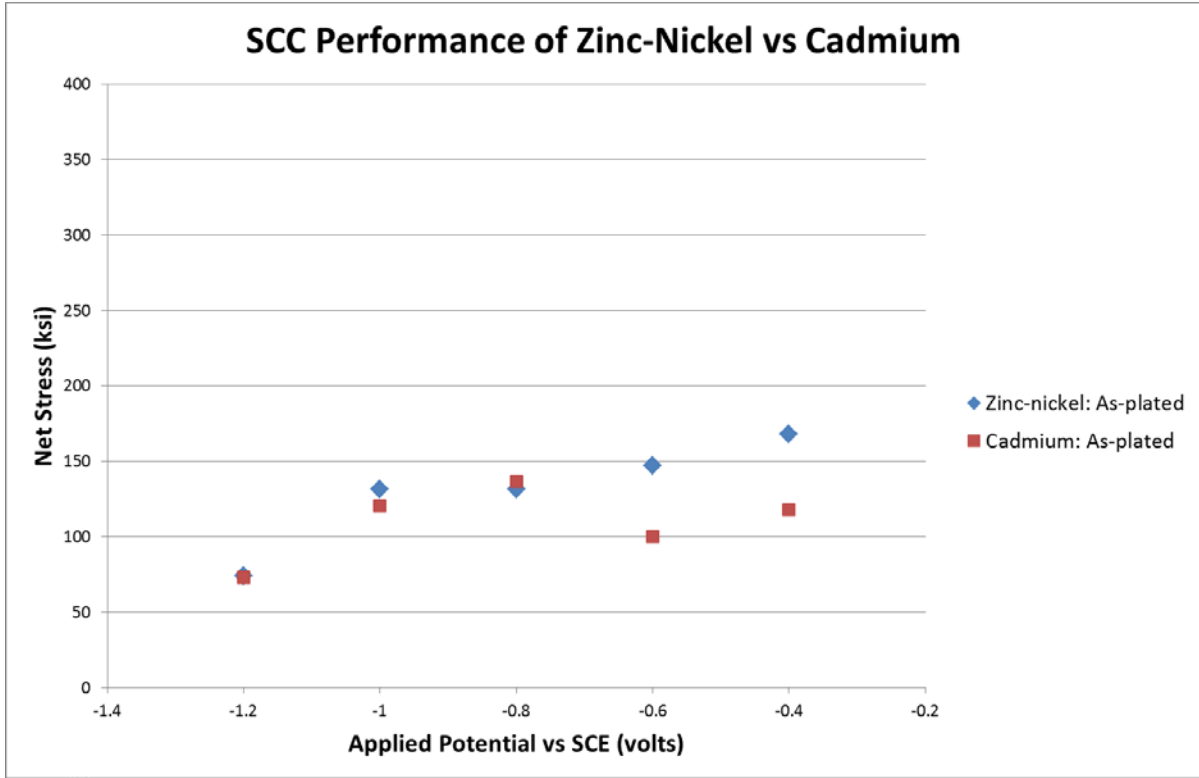


Figure 7. SCC Performance of Zn-Ni Compared to Cadmium on 4340 Steel

Figure 8 shows the SCC performance of zinc-nickel and cadmium with MIL-PRF-23377 Class C primer only and with both primer and MIL-PRF-85285 Type I gloss white topcoat. The figure shows that the impact of the primer and topcoat varied for each sacrificial coating, but overall, the full protective system was superior for each.

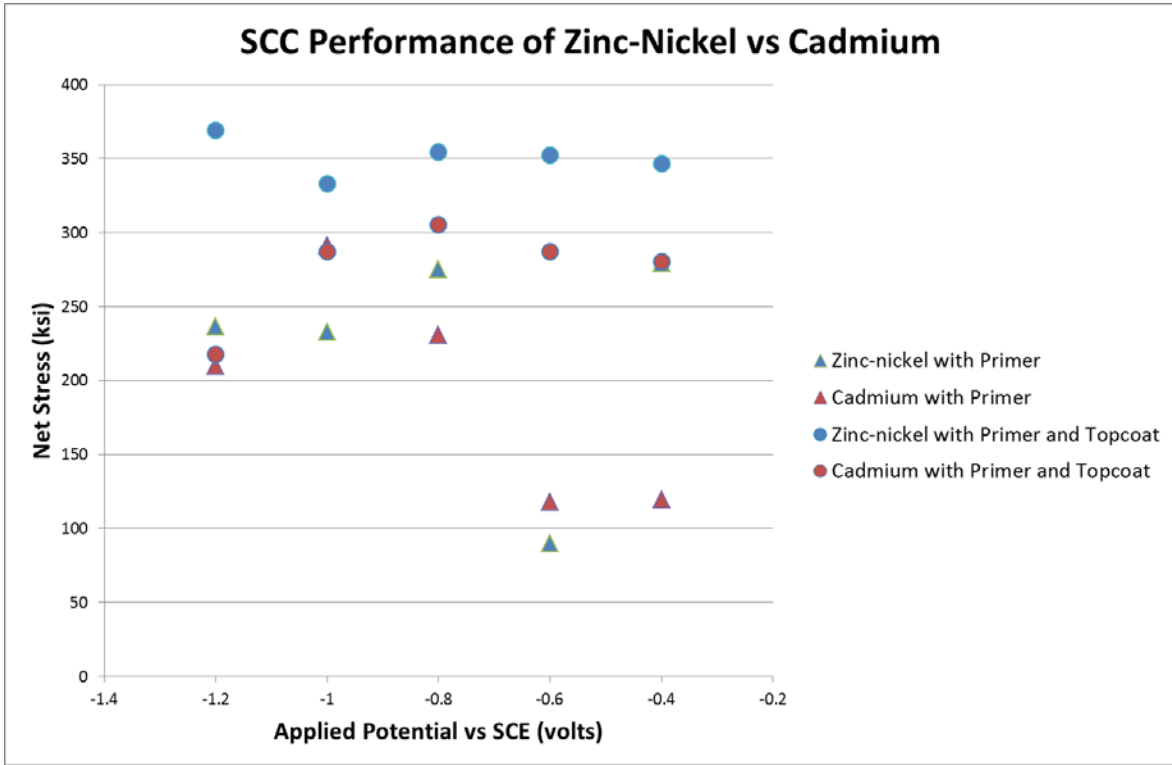


Figure 8. SCC Performance of Zn-Ni Compared to Cadmium with Primer and Topcoat on 4340 Steel

## CONCLUSIONS

The following conclusions can be drawn from the data:

1. IZ-C17+ zinc-nickel, like cadmium, provides a significant increase in corrosion fatigue life compared to uncoated 4340 steel.
2. IZ-C17+ zinc-nickel corrosion fatigue performance is similar to cadmium with a full protective coating system and possibly slightly reduced at lower stress levels without organic coatings.
3. The primer and topcoat have additive, positive effects on SCC resistance for cadmium and IZ-C17+ zinc-nickel.
4. IZ-C17+ zinc-nickel SCC performance is at least as good as cadmium by itself and with the full protective coating system.

## RECOMMENDATIONS AND LESSONS LEARNED

The following recommendations are offered to support the maturation of the zinc-nickel coating technology and extend the understanding of the effects of primer and topcoat on overall sacrificial coating performance:

1. Repeat the SCC and corrosion fatigue testing using the new IZ-C17+ zinc-nickel plating line being installed at FRC-Southeast using conformal anodes. Test specimens in this report were plated without conformal anodes which may have affected performance.
2. Assess the SCC and corrosion fatigue impact of zinc-nickel and cadmium on additional substrates of interest such as Aermet 100 and PH 13-8 steels.
3. Assess the impact of additional implemented and developmental primers and topcoats on the SCC and corrosion fatigue performance of zinc-nickel, cadmium and IVD aluminum.
  - a. MIL-PRF-85582 Class C primers
  - b. MIL-PRF-85285 Type IV gloss white topcoats
  - c. MIL-PRF-23377 Class N primers
  - d. Aluminum-rich primers
  - e. Non-isocyanate topcoats
4. Assess the impact of coating thickness on SCC and corrosion fatigue. Standard thicknesses were used for testing in this report.
5. Assess the impact of defects in the coatings on SCC and corrosion fatigue. Results in this assessment may be heavily influenced by the barrier properties of the primer and topcoat.
6. Consider SCC and corrosion fatigue impacts during the development of primers and topcoats, with a long-term goal to optimize performance for the reduction of both.

The following lessons learned are offered for future assessments:

1. Additional data points for the SCC and corrosion fatigue tests should be taken for each coating system to improve the statistical validity of the results. It is suggested to complete at least three replicates for each SCC voltage and six replicates for each fatigue stress level, with a minimum of five stress levels per assessment.



REFERENCE

1. Lee, E.U., et al., Coated 4340 Steel, NAWCADPAX/TR-2103/252, 26 August 2013.

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