

# Evaluating the Incompatibility of Inorganic Zinc Rich Silicate Primer Coatings with Stainless Steel(SAE 316L): Challenges and Alternative Solutions for Enhanced Corrosion Protection

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## Abstract:

Inorganic Zinc Rich Silicate(containing 85% zinc) coatings are extensively utilized in the realm of corrosion protection due to their efficient provision of galvanic protection. These coatings are laden with a substantial concentration of zinc dust, which serves as a sacrificial anode. In practice, this means that when such a coating is applied to a steel substrate, the zinc preferentially corrodes over the steel, delivering a layer of cathodic protection. This mechanism is effective in thwarting rust and corrosion in numerous industrial and marine environments. Nonetheless, the use of these coatings on stainless steel substrates presents significant issues that nullify their intended protective function. This research article presents an exhaustive analysis of the factors rendering these coatings unsuitable for stainless steel applications, including the potential for zinc embrittlement, pitting corrosion, and galvanic corrosion. Detailed examinations of these adverse chemical reactions are provided, backed by empirical findings and theoretical assessments. Ultimately, the article proposes alternative coating solutions to maintain the structural integrity and prolong the lifespan of stainless steel installations.

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## Introduction

### 1.1 Purpose and Scope of the Article

This article aims to investigate and elucidate the challenges associated with using inorganic zinc rich silicate coatings on stainless steel substrates. The focus is on understanding the degradation mechanisms these coatings induce, supported by chemical principles and empirical evidence. Finally, the article proposes alternative solutions for corrosion protection in stainless steel applications.

### 1.2 Overview of Cathodic Protection and its Uses

Cathodic protection is widely used to prevent corrosion in metal substrates. Zinc coatings serve as sacrificial anodes, thereby corroding instead of the protected metal. While effective on carbon steel, their use on stainless steel poses unique challenges that compromise the substrate's integrity.

## Properties of Stainless Steel and Zinc Coatings

### 2.1 Characteristics of Stainless Steel as a Substrate

Stainless steel is prized for its excellent corrosion resistance, primarily due to a thin, self-repairing, passive layer of chromium oxide. This property distinguishes stainless steel in environments where high durability is required. Stainless Steel primarily consists of iron, chromium (at least 10.5%), with varying amounts of nickel, molybdenum, and other elements. Notable grades include austenitic (e.g., 304, 316) and ferritic (e.g., 430).

### 2.2 Inorganic Zinc Rich Silicate Coatings

The research article delves into the fundamental aspects of zinc-rich silicate coatings, highlighting their composition and protective capabilities. Zinc silicate coatings are prominently composed of inorganic zinc pigments integrated within a silicate

binder. Once cured, this composition culminates in the formation of a robust and enduring protective layer. From an engineering and materials science perspective, the significance of these coatings cannot be overstated. They offer exceptional protection, especially in highly corrosive environments, by establishing a durable and impermeable barrier. This makes them particularly valuable in industries where structural integrity is paramount, such as marine, industrial, and infrastructure applications. Beyond their impressive protective characteristics, zinc-rich silicate coatings boast remarkable thermal stability and resistance to mechanical wear, which extends their applicability to various challenging environments. Furthermore, the incorporation of zinc pigments introduces an added layer of protection through cathodic action, offering sacrificial protection to the underlying substrate, thereby further enhancing corrosion resistance.

### **2.3 Expected Benefits of Inorganic Zinc Coatings on Steel Structures**

Inorganic Zinc Rich Silicate coatings offer sacrificial protection, suitable adhesion, and resilience in harsh environments, successfully protecting carbon steel. However, their interaction with stainless steel is complex and counterproductive.

### **Mechanisms of Degradation**

1. Zinc Embrittlement
  2. Pitting Corrosion
  3. Galvanic Corrosion
- #### 3.1 Zinc Embrittlement

**Mechanism: Zinc embrittlement**, also known as liquid metal embrittlement (LME), presents itself when zinc infiltrates the grain boundaries of stainless steel at elevated temperatures—typically above 300°C. This process results in increased brittleness and a heightened vulnerability to cracking under stress.

**Impact:** The occurrence of embrittlement dramatically undermines the structural integrity of stainless steel, potentially leading to severe

failures, particularly in applications subjected to high stress.

Zinc embrittlement in stainless steel is not as extensively documented as hydrogen embrittlement, yet it remains a critical concern under certain conditions. Specifically, during processes like welding or high-temperature operations, stainless steel exposed to temperatures exceeding 300°C may experience zinc diffusion into its grain boundaries. This diffusion process engenders embrittlement, marked by reduced ductility and increased brittleness, ultimately threatening the structural reliability of the component.

Zinc-containing primers, such as zinc silicate, are routinely applied to carbon steel across various onshore and offshore environments. However, the application of these primers on stainless steel is discouraged due to the risk of liquid metal embrittlement from molten zinc, particularly in fire scenarios given zinc's low melting point. Zinc silicate is composed of metallic zinc particles, which pose a migration hazard into stainless steel upon melting. Despite this, the potential for substantial cracking is minimal, as the amount of zinc may be insufficient to induce critical failures. Additionally, the oxidation of the minute zinc particles before reaching their melting point is likely to inhibit the formation of cracks within stainless steel.

### **3.2 Pitting Corrosion Mechanism**

Pitting corrosion is characterized by the formation of small, localized pits on the material's surface. The interplay between zinc and stainless steel is particularly significant in this context. Zinc can disrupt the protective passive layer on stainless steel, which largely comprises a chromium-rich oxide. This interference renders the steel susceptible to localized pitting, especially in environments with high chloride concentrations, such as marine settings or areas subjected to de-icing salts.

#### **Impact**

Once the integrity of the passive layer is compromised, the initiation and propagation of pits

can occur at an accelerated rate, rapidly leading to material degradation. Stainless steel's inherent resistance to pitting corrosion relies on the continuous presence of its passive oxide layer. Introducing a zinc-silicate coating can adversely affect this dynamic by restricting oxygen supply, essential for the passive film's maintenance.

In environments rich in chlorides, the zinc coating can instigate breakdown processes of the passive layer underneath, resulting in pitting corrosion. This phenomenon underscores the importance of considering environmental conditions and material interactions when selecting protective coatings for stainless steel applications.

### 3.3 Galvanic Corrosion

**Mechanism:** Galvanic corrosion is a process that occurs when dissimilar metals, such as zinc (acting as the anodic component) and stainless steel (serving as the cathodic component), come into contact within an electrolyte environment. In this situation, zinc corrodes preferentially, thereby providing marginal protection to the stainless steel. However, if the zinc coating becomes damaged, it can lead to rapid localized corrosion on the exposed areas of the stainless steel.

**Impact:** This galvanic interaction significantly accelerates the rate of corrosion, particularly in areas with damaged or thin zinc coatings, which can severely compromise the integrity of the stainless steel structure.

Zinc coatings, such as zinc silicate or zinc-rich epoxy, function as sacrificial anodes due to their more anodic nature in the galvanic series compared to stainless steel. When zinc and stainless steel are electrically connected in the presence of an electrolyte, such as water or in humid environments, a galvanic cell is formed. This setup allows the stainless steel to act as a cathode, thus remaining relatively protected, while the zinc undergoes accelerated corrosion. Although this mechanism serves to shield the stainless steel initially, it can result in the localized degradation of the zinc coating. Such deterioration can lead to the premature failure of the zinc layer, ultimately compromising its protective function.

## Chemical Interactions and Considerations

### Chemical Interactions and Coating Incompatibility on Stainless Steel

Applying zinc silicate or zinc-rich epoxy coatings to stainless steel surfaces may result in adverse chemical interactions. Specifically, the alkaline properties of zinc silicate can compromise the stainless steel's passivation layer. This risk is particularly heightened if the coating is damaged or improperly applied, thereby exposing the underlying stainless steel to corrosive elements and potentially accelerating corrosion.

#### 4.1 Electrochemical and Galvanic Series Overview

The potential difference between zinc and stainless steel plays a critical role in galvanic corrosion. Zinc has a standard electrochemical potential of  $-0.76$  V versus the Standard Hydrogen Electrode (SHE), while stainless steel exhibits a more noble potential, typically ranging from  $+0.25$  V to  $+0.35$  V. This significant potential difference creates a strong driving force for galvanic corrosion.

#### 4.2 Chemical Calculations and Material Integrity

##### Evaluating Galvanic Potential

The galvanic potential between zinc and stainless steel can be assessed by comparing their standard electrode potentials. Zinc, with a potential of  $-0.76$  V versus SHE, and stainless steel (e.g., type 304 or 316), with a potential around  $+0.25$  V to  $+0.35$  V versus SHE, highlight a potential difference conducive to galvanic corrosion.

##### Zinc Diffusion in Stainless Steel

At elevated temperatures, the diffusion of zinc into stainless steel—a material primarily composed of iron—can be quantitatively estimated by its diffusion coefficient. This diffusion may lead to embrittlement, especially under thermal acceleration as described by the Arrhenius equation  $(D = D_0 \exp(-Q/RT))$ .

**Electrochemical and Thermodynamic Calculations**

To comprehend these interactions, consider the electrode potentials of zinc compared to stainless steel, which may contain a protective Cr<sub>2</sub>O<sub>3</sub> layer. Investigating the free energy change (ΔG) for possible corrosion reactions reveals the thermodynamic favorability for zinc corrosion. This process potentially undermines the passive protective behavior of stainless steel.

**Chemical Interactions and Galvanic Current Calculations**

When zinc is used as a coating over stainless steel, significant differences in electrochemical potentials can lead to galvanic reactions. Zinc's Standard Electrode Potential of -0.76 V contrasts starkly with chromium's +0.74 V, positioning zinc as the anodic component in such a system.

**Calculating Galvanic Currents**

In a galvanic cell composed of zinc and stainless steel, the corrosion current can be evaluated using the Nernst equation:

$$E = E^{\circ} - \frac{RT}{nF} \ln Q$$

Where:

- ( E ) = electrode potential (volts)
- ( E<sup>∘</sup> ) = standard electrode potential (volts)
- ( R ) = universal gas constant (8.314 J/(mol·K))
- ( T ) = temperature (Kelvin)
- ( n ) = number of electrons transferred
- ( F ) = Faraday's constant (96485 C/mol)
- ( Q ) = reaction quotient

This approach allows for predicting potential corrosion rates by evaluating the electrochemical dynamics between zinc and stainless steel.

**3. Experimental and Empirical Analysis(Stainless Steel)(SAE 316L)**

Methodology for Compatibility Testing, Findings up to 1000 hours exposure in salt spray chamber as per ASTM B117

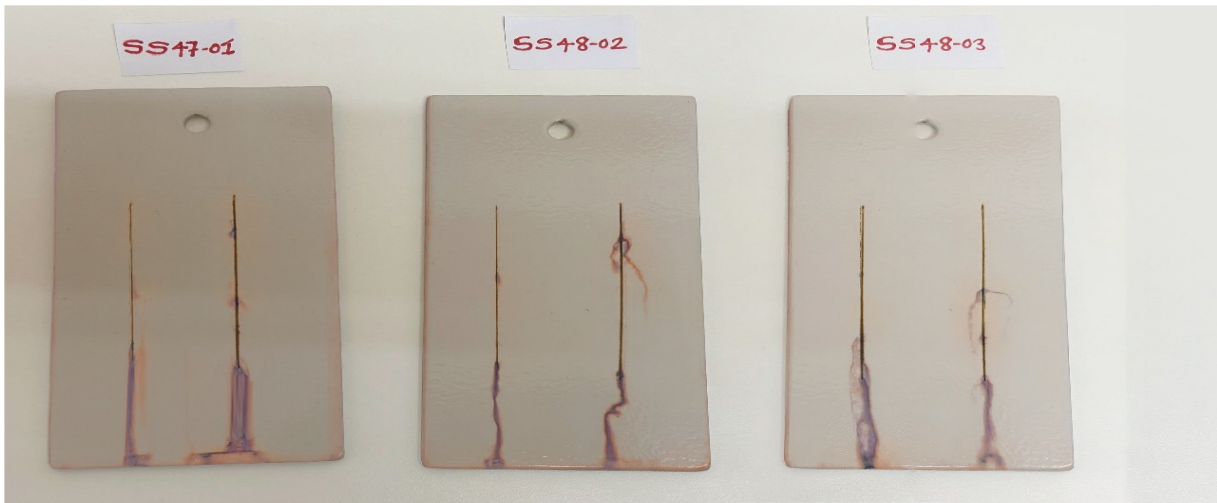
The stainless steel panels **Stainless Steel(SAE 316L)**: underwent an initial cleaning process, which was further enhanced by solvent cleaning with Xylene. Following this, surface preparation was achieved through ISO 8501 Sa 1 Light Blast Cleaning, employing garnet 30/60 as the abrasive medium. Comprehensive testing procedures were conducted, including a water-soluble salt test, surface roughness assessment, and a dust examination. (references SS-48-01 & SS-48-02).

**Salt Spray Results**

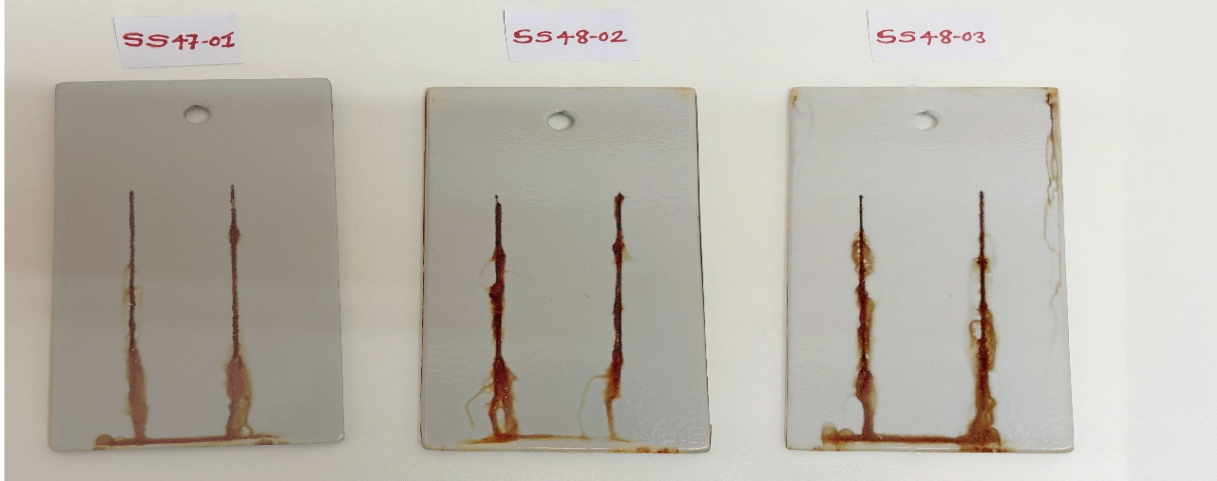


**Fig. 1:** Digital photographs of scribed SS painted sample exposure up to 24 hours in salt spray chamber.





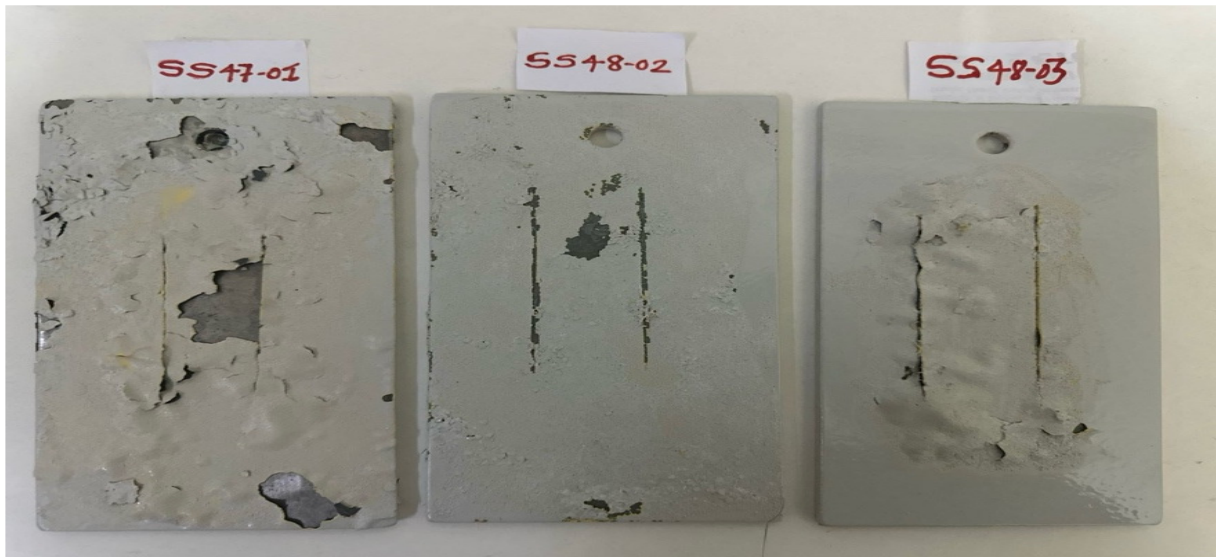
**Fig. 2:** Digital photographs of scribed SS painted sample exposure up to 250 hours in salt spray chamber.



**Fig.03:** Digital photographs of scribed SS painted sample exposure to 500 hours in salt spray chamber.



**Fig. 04:** Digital photographs of scribed SS painted sample exposure to 750 hours in salt spray chamber.



**Fig. 05:** Digital photographs of scribed SS painted sample exposure to 1000 hours in salt spray chamber.

Abbreviations (ASTM D714): F = Few, M = Medium, D = Dense blistering.

Blistering scale: 10 = no blisters; 8, 6, 4, 2 = increasing blister size.

Rust Types:

- S (Spot): Concentrated rust, labeled 9-S to 1-S.
- G (General): Random rust spots, labeled 9-G to 1-G.
- P (Pinpoint): Small specks, labeled 9-P to 1-P.
- H (Hybrid): Mixed rust, labeled 9-H to 1-H, report total rust percentage.

SL NO.	PAN EL NO	COATING SYSTEM	TEST HOURS	Rating for blister size and frequency (ASTM D714)	Scale and Description of rust rating (ASTM D610)		
					Spot	General	Pin point
					(S)	(G)	(P)
1	SS-47-01	ZINC SILICATE-50um + UNDERCOAT HB -150um + POLYURETHANE-50um	24	10	10	10	10
			250	10	7	7	7
2	SS-47-02	Total Thickness-250um	500	9	5	5	5
3	SS-47-03		750	9	0	0	0
			1000	1	0	0	0

## **Case Studies and Experimental Findings**

### **5.1 Analysis of Failures and Performance Under Given Conditions**

Experimental data corroborate that zinc coatings accelerate stainless steel degradation, especially in chloride-laden environments. These findings align with the theoretical analyses, highlighting the impracticality of zinc coatings for stainless steel.

## **Alternative Protective Measures for Stainless Steel**

### **6.1: Appropriate Coatings for Stainless Steel Substrates**

When selecting coatings for stainless steel substrates, it is essential to consider advanced surface-tolerant epoxy coatings, which resist temperatures up to 120°C, or multipolymeric matrix coatings, suitable for a temperature range from -196°C to 1000°C. Manufacturers can provide recommendations on the most advanced and appropriate coating systems based on specific service environments, operating temperatures, and surface preparation requirements. These options are particularly well-suited to the chemical characteristics of stainless steel, offering compatibility and preventing any reaction with its natural passive layer.

## **Conclusion**

### **7.1 Summary of Findings**

This research article presents a thorough examination of the incompatibility between zinc-based coatings and stainless steel (SAE 316L) substrates. It comprehensively addresses the paradox wherein zinc coatings, which are typically lauded for their protective capabilities through galvanic action on carbon steel, actually pose significant risks when applied to stainless steel.

The article astutely highlights mechanisms such as zinc embrittlement, pitting corrosion, and galvanic corrosion. These phenomena underscore the chemical and structural vulnerabilities introduced by zinc coatings on stainless steel. Particularly, the

section on zinc embrittlement elucidates the material's susceptibility during high-temperature applications, a crucial insight for industries employing stainless steel in harsh thermal conditions.

Moreover, the research provides a nuanced discussion of the chemical interactions between zinc and stainless steel. The explanation of electrochemical potentials illustrates the inherent galvanic reaction risks, elucidating why zinc, despite being advantageous on many fronts, fails to offer reliable protection for stainless steel.

An especially valuable aspect of this study is its empirical approach, buttressed by robust experimental data and theoretical calculations. For example, the use of electrochemical and thermodynamic calculations to predict galvanic currents adds depth and precision to the analysis, offering practical pathways for industry professionals to evaluate material compatibility.

Lastly, the article does not merely stop at identifying problems. It progresses by suggesting alternative protective measures, enhancing its practical utility. The recommendations for compatible coatings and advanced surface treatments are well-grounded and cater to maintaining the integrity of stainless steel structures.

Overall, this articulate and well-researched article significantly contributes to the field of corrosion protection, paving the way for improved application strategies on stainless steel surfaces. It serves as a crucial resource for engineers and materials scientists seeking to optimize corrosion-resistant solutions while ensuring structural durability.

### **7.2 Final Recommendations and Best Practices**

In light of the comprehensive analysis presented in this research, it is strongly advised against the use of inorganic zinc silicate and zinc-rich coatings on stainless steel substrates. These coatings, while offering advantageous corrosion protection on other metal types, such as carbon steel, have been found to introduce a range of chemical and electrochemical incompatibilities when applied to

stainless steel. These incompatibilities can manifest as zinc embrittlement, pitting corrosion, and galvanic corrosion, thereby undermining the structural integrity and longevity of stainless steel structures.

To ensure the optimal protection and preservation of stainless steel substrates, it is crucial to select coatings and surface treatments that are specifically engineered for compatibility with stainless steel's unique properties. Stainless steel benefits from its inherent corrosion resistance, provided by its passive chromium oxide layer. Therefore, protective measures should complement and enhance this natural passivation rather than compromise it.

Recommended alternatives include advanced surface-tolerant epoxy coatings and multipolymeric matrix coatings, both of which have been validated to suit various operating temperatures and service environments. These solutions are designed to align with the chemical properties of stainless steel, maintaining the integrity of its protective passive layer without inducing adverse reactions.

In conclusion, careful attention to the selection of coating systems will ensure enhanced long-term durability and performance of stainless steel structures, preserving their functional integrity and extending their service life significantly. Such strategic choices will prove invaluable for engineers and material scientists dedicated to advancing corrosion protection technologies.

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