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Assessing Coating Degradation Along a Scribe in a Ballast Tank Environment

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ABSTRACT

This study evaluates the suitability of corrosion testing methods for analyzing the scribe performance of coated steel in environments resembling ballast tanks. While the fog/dry test effectively accelerates corrosion on bare steel, it falls short of replicating ballast tank conditions for coated scribed steel. It shows significant variability, which limits precise evaluation. A procedure previously developed at AMACORT, the AMACORT CIFD-01 test procedure, proves more reliable for scribe performance analysis, offering greater precision and repeatability.

This study also explores the effects of surface cleanliness and roughness on coating performance using the fog/dry test method. Fog/dry testing is used as it is widely recognized and commonly applied, whereas the AMACORT CIFD-01 protocol requires significantly more handling. Increased salt contamination correlates with a greater mean creep, which becomes significant when PSPC₁₅ standards are being exceeded. Regarding dust contamination and surface roughness deviations, no significant effects were observed, like those seen with increased salt contamination. A dust contamination increase contributes to performance degradation but not significantly, nor do surface roughness deviations. These findings underscore the importance of selecting appropriate test methods and maintaining adherence to surface cleanliness and roughness standards, in particular salt contamination, to ensure optimal coating performance and adhesion durability.

1 Introduction

Corrosion remains an ongoing challenge for ships as long as steel continues to be a construction material in shipbuilding. Among the most extreme corrosive environments within a vessel, ballast tanks stand out due to, for instance, their wet/dry effect. If ships are constructed with ballast tanks, corrosion in these areas will persist, necessitating regular evaluation and maintenance. Given that ships are coated to mitigate corrosion, this challenge can also be framed as the continuous need to assess the performance and durability of coatings in ballast tanks. According to the International Maritime Organization (IMO) regulations, when a vessel surpasses five years of service, ballast tank inspections are mandated minimally two times within a five-year peri-

od. This article focuses on ship ballast tanks as a critical environment for corrosion protection. Two key topics will be explored here. First, the impact of accelerated corrosion test methods on scribed coated specimens is examined, as this approach is commonly used to assess coating performance. Second, while coating thickness has already been evaluated by Willemen et al. [1], the focus is shifted to the effects of surface cleanliness and surface roughness; factors whose importance was established before [2].

The scribe test is a method to evaluate the loss of adhesion of coatings for accelerated and atmospheric exposure tests with the purpose of investigating coating performance when subjected to corrosive environments [3]. This test allows us to evaluate the performance of a coating in protecting the underlying substrate from cor-

rosion, focusing on the phenomenon known as creep in this context. Here, creep refers to the degree of corrosion (usually measured in mm) emanating from a scribe. This creep can appear as visible rust formation as the coating fails and comes loose from the substrate. This creep can also be seen as blisters. In this case, the electrolyte can pass under the coating through weak and damaged points in the coating along the scribe. This allows micro-corrosion cells that naturally form below the coating to change into anodic sites, also called crevice corrosion, and form blisters. These blisters can then be associated with corrosion, and even further, the loss of adhesion, also specified as anodic blistering by Kibler [4].

To have a good reference of the creep in ballast tank accelerated and atmospheric exposure tests, three accelerated corrosion protocols were chosen from the study of Willemen [5]. This implies a filled ballast tank protocol using immersion, an empty ballast tank protocol where the environmental conditions fog as well as dry take place and a cyclic combination protocol of both filled and empty ballast tanks, using the cyclic regime of a 50% immersed and a 50% empty ballast tank, representing the average ballast tank environmental condition. The latter is named AMACORT CIFD-01 (Cyclic Immersion Fog Dry). The three studies, also examined in the reference study, were selected to enable a broader comparison between the two works by relating the creep results obtained in the present study to the weight loss results reported in the reference study.

Besides a defined service environment, a standard specifying the normal substrate surface parameters also needs to be established, from which deviations will eventually be introduced to investigate their effect. In this study, the IMO PSPC₁₅ standard [6] is used, which specifically addresses dedicated seawater ballast tanks in all types of ships and double-side skin spaces of bulk carriers. For the surface cleanliness, it depicts a water-soluble salt limit equivalent to $\text{NaCl} \leq 50 \text{ mg/m}^2$ of sodium chloride, and for the dust quantity rating "1" for dust size class "3", "4", or "5" [7] (Reference standard: ISO 8502-3:1993). Lower dust size classes are to be removed, if visible on the surface to be coated without magnification. In respect of the surface roughness profile, the IMO specifies a coating thickness range of 30–75 μm . All the above parameters are evaluated by first inspecting the creep when in conformity with PSPC₁₅ and subsequently by deviating from PSPC₁₅ to investigate the effect.

When deviating from the water-soluble salt limit to higher levels than allowed in the PSPC₁₅ standard, the origin of the formation of blistering will not only be anodic blistering but also osmotic blistering is to be expected. According to Patrick Cassidy and Michael Kibler the typical contaminants that lead to osmotic blistering are salts, especially in marine environments. As water migrates under the coating through weak and damaged

points in the coating along the scribe, the water encounters soluble salt particles that dissolve in the water. This slows down the flow rate of the amount of water leaving the surface, whilst the flow rate of water coming to the steel surface stays the same. When the amount of water builds up, the adhesive strength of the coating fails due to hydraulic pressure and a blister is formed.

As the investigated failure is adhesion, the way a coating is applied is important for coating performance, more specifically, surface cleanliness and surface roughness. This study investigates this phenomenon in the context of a ballast tank environment. The motivation for examining the service environment of a ship's ballast tank is that extending the coating's lifespan can significantly reduce maintenance costs for the ship owner [8].

2 Material & Methods

2.1 Accelerated testing protocols in benchmarking creep

Creep was used as the benchmark to evaluate failure in adhesion. Creep was first studied using three relevant accelerated corrosion testing protocols designed to simulate a ballast tank, which are described in detail by Willemen et al. [5]. Briefly, in the first protocol, a set of scribed samples was immersed in a basin filled with artificial seawater with the temperature kept "au bain-marie" at 40 °C – 41 °C. In the second protocol (the fog/dry test) an empty ballast tank was simulated in which the scribed samples were subjected to a cyclic fog/dry exposure of 4 hours of fog at 25 °C followed by 2 hours dry-off at 35 °C. Finally, an in-house developed, cyclic combination protocol (AMACORT CIFD-01, Cyclic Immersion Fog Dry) was used, simulating both filled and empty ballast tanks, with a cyclic regime of a 50% immersed and a 50% empty ballast tank, representing the average ballast tank environmental condition. All three protocols were performed for a total period of 12 weeks (14 periods of 6 days) or 2016 hours.

Creep outcome was evaluated, as well as the weight loss. As for the determination of the reference creep, two conditions were used; on one hand, the blister formation is excluded, and on the other hand, blister formation is included.

2.2 Surface parameters contamination

The IMO PSPC₁₅ standard [6] was put forward as the reference standard in this study, describing surface cleanliness, in terms of salt and dust, as well as surface roughness. This reference was used to benchmark creep when in conformity to this standard. Deviation from this standard, non-conformity, was investigated to evaluate the individual effect on the adhesion failure mechanism along a scribe.

The accelerated corrosion testing protocol used in the variance of the surface cleanliness and surface roughness was the cyclic fog/dry exposure protocol. This is based on the conclusion of Willemen [5] that immersion exposure cannot be considered as an accelerated test protocol, that the fog/dry test is a true competitor of the AMACORT CIFD-01 and that the fog/dry test is even at an advantage due to its replicability. Other reasons to use fog/dry testing are that fog/dry testing is widely recognized and commonly applied, whereas the AMACORT CIFD-01 protocol requires significantly more handling and labor. All scribed samples were subjected to a fog/dry exposure total period of 2016 hours.

Soluble salt

IMO PSPC₁₅ prescribes a water-soluble salt limit equivalent to NaCl ≤ 50 mg/m² of sodium chloride [6]. To study the effect of salt contamination, a quantity of salt was applied on the surface, either below the max reference value, at around 20 mg/m² ($\pm 15\%$), around the max reference value of 50 mg/m² ($\pm 15\%$), and above this value, around 100 mg/m² ($\pm 15\%$). To this end, a custom-cut cloth was soaked in a water bath with the chosen salt percentage, drained and subsequently pressed gently on the surface of the coupon. This resulted in a uniform salt distribution.

Verification of this application procedure is done with the patch cell test or Bresle test (TQC, The Netherlands), following the guidelines outlined in ISO 8502-6 and ISO 8502-9 standards. In this test, a known quantity of deionized water was added to a patch to cover a known area of the surface. After a set amount of time, the water was removed from the patch and put into the conductivity meter to determine the conductivity (Elcometer type 138E, TQC, The Netherlands). The higher the conductivity, the more salts were present on the substrate. It should be noted that this verification method is a destructive test, and that the tested specimen can subsequently not be used for further investigation.

Dust

IMO PSPC₁₅ prescribes that dust of ISO dust size classes 3, 4 and 5 should only be present in an amount of ISO rating 1. Lower dust size classes should be removed if visible on the surface without magnification [6].

To realise the dust contamination evenly spread on the coupons, they were placed on a tared scale. To obtain a good distribution over the surface, the dust was spread through a sieve, used for household kitchenware, at a height of 20 cm (which allowed for a good distribution and little loss of excess dust). Easily distinguishable amounts of dust contamination of 110 mg, 220 mg and 330 mg were chosen for further experi-

mentation. Additionally, the size of the dust particles was varied as well. Standardized sizes of dust [9] were used (Particle Technology, Hatton, Derbyshire, England), with grain sizes of 50 – 100 μm and 100 – 500 μm . For each combination of amount and size of dust, four replicates were used.

Surface roughness

The surface should be blasted to an ISO roughness standard Sa 2^{1/2}, with a roughness profile between 30 and 75 μm [6, 10]. To investigate the effect of this parameter, steel coupons were pretreated to different sandblasting regimes. Firstly, as a reference state conforming to the standard PSPC₁₅ requirements, GH50 grit was selected for blasting. This is a sharp and edged abrasive with a size of 0.2-0.6 mm. To measure the degree of roughness, a roughness comparator 125 G was used (Figure 1), which is specially designed to check the roughness of steel surfaces that have been blast cleaned to cleanliness grades Sa 2^{1/2} before painting.

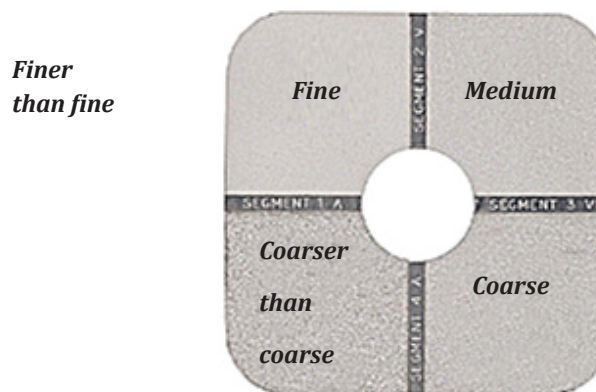


Figure 1 Surface roughness comparator with categories of roughness

Reference samples exhibited a profile equal to segment 2 and up to, but excluding segment 3, and were categorized as medium on the roughness comparator (comparable to a surface roughness of around 60 μm). This aligns well within the prescribed limits set by PSPC₁₅, with a Rz value ranging between 30 and 75 μm . Coupons with a surface roughness exceeding the acceptable limits were prepared using grit size GH18, further defined as 'rough' and categorized as "coarse" on the roughness comparator. This corresponds to an Rz of around 100 μm and exceeds the PSPC₁₅ roughness criteria. Finally, for a surface that is too smooth and falls below the PSPC₁₅ criteria, blasting was conducted using glass beads, leading to a profile comparable to segment 1 and up to, but excluding segment 2, categorizing as 'fine' on the roughness comparator and comparable to a roughness of around 25 μm .

2.3 Scribed specimens

Samples used were grade A steel coupons of 150 mm × 100 mm with a 3 mm thickness. They all received the same basic pre-treatment. First, they were soaked in standard kitchen vinegar, after which they were scrubbed using a sponge. Subsequently, they were rinsed with deionized water, dried with kitchen paper, and sandblasted. After this basic pre-treatment, they were either coated or they received an additional manipulation before coating, as described above.

The paint system used was a two-layer HEMPADUR 45143 epoxy coating (Hempel, Denmark), which is composed of base component HEMPEL 45141 and curing agent HEMPEL 97430.

The application procedure was as follows: a grid was placed on top of a collection tray, with three coupons positioned on it, of which the middle one was to be painted. A small amount of paint was applied to the middle plate, which was then spread to the desired film thickness using a TQC Bird film applicator of 150 mm in length (TQC, The Netherlands), to ensure uniform application. For the application of the first layer, the side of the applicator with a 200-micron gap was used. For the second layer, a 400-micron gap was employed, allowing the meantime dried first paint layer to be supplemented with an additional wet layer, bringing the total thickness, partly wet, to 400 microns.

The scribe was applied with the Machu Scratching Tool Professional (TQC, type number VF8605 – TYPE CC3000) in combination with a holder for the plate and an alignment guide. The 9 cm scribe had to penetrate

the two-layered protective coating down to the metal, leaving a bright line. Multiple cuts were needed, always performed along the same line. By keeping the cutting wheel of the scratch tool against the alignment guide, a straight scratch was consistently made in the centre of the plate. Lines were also marked on the guide to ensure that all scratches are of equal length.

The total number of specimens prepared for the creep benchmarking study was 39 samples. For the immersion phase 3 test specimens were scribed. For the fog/dry exposure, a total of 6 test specimens were considered. For the AMACORT CIFD-01 protocol, the amount was 30 test specimens. For the non-conformity testing procedure, four samples were used per surface treatment.

For each variation of each surface parameter, 4 specimens were prepared as replicates.

2.4 Scribe evaluation method

Evaluation of the undercutting or creep in a scribe test occurred visually, resulting in a value describing the extent of the failure measured from the edge of the original scribe track. This value is called mean creep and is obtained as follows.

As illustrated in Figure 2, the extent of failure, denoted as “dt,” was measured at 15 positions along the scribe. In the left illustration, the assessment includes blister formation, whereas in the right illustration, only the visibly corroded areas are considered. Subsequently, the measured extent of failure, “dt,” was adjusted by subtracting the initial scribe width of 1 mm, denoted as

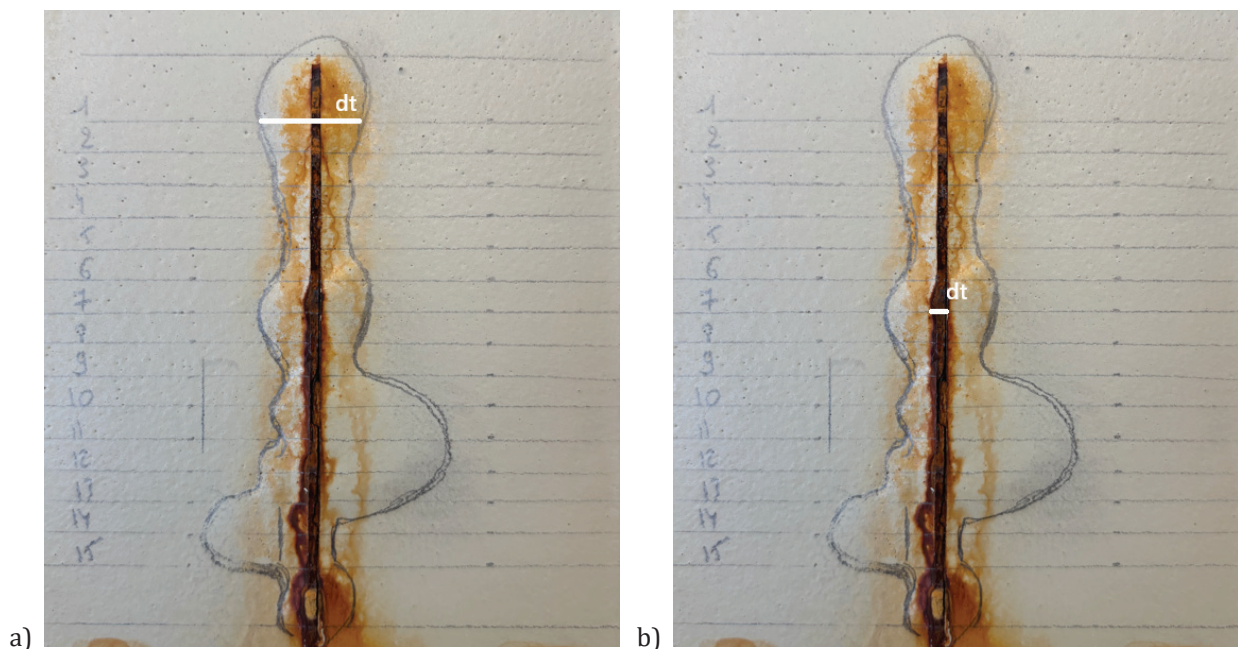


Figure 2 a) Illustration of the extent of failure measured with blister formation of an exposed fog/dry coupon at position 1 along the 9 cm long scribe; b) Illustration of the extent of failure measured without blister formation of an exposed fog/dry coupon at position 7 along the 9 cm long scribe

“d0.” This adjustment isolates the failure that occurred exclusively because of the testing process. The resulting value was then divided by 2, as creep is evaluated based on the extent from a single edge. Finally, the mean creep was determined by averaging the individual creep measurements obtained from the 15 positions.

Mean creep was measured and subsequently scored in a rating, both in accordance with ASTM standard D1654-05 [11], grading the failure rate from 10 to zero, where “10” involves no mean creep from the scribe to “0” implicating 16 mm or more mean creep from the scribe. Mean creep was always noted in two ways: visible rust creep, excluding blisters, as well as creep including blisters.

Corrosion scribe tests are typically evaluated using rating systems rather than relying solely on precise measurements. Ratings provide a standardized and practical method for assessing corrosion performance. While ratings are effective for delivering consistent evaluations, they are less precise than direct measurements. However, combining both approaches enhances the analysis. Measurements offer a more detailed quantification of specific phenomena, which can be essential for a deeper understanding of corrosion behaviour. To complement the ratings, mean creep measurements were presented in a box-and-whisker plot, which conveys both the distribution and the central tendency of the data. This combined approach allowed for a more comprehensive and accurate interpretation of the test results.

2.5 Statistical analysis

Data were analysed in the open statistical software environment R, version 4.4.1 of R Core Team from 2024, [12] with a one-way or two-way ANOVA followed by a pairwise comparison with a Tukey Honest Significant Differences test. Packages stats [12], rstatix [13] and EnvStats [14] were used.

3 Results

3.1 Bormal scribe performance in accelerated corrosion testing protocols

In Willemen et al. [5], uncoated steel was used to evaluate the acceleration factor obtained from the simulated aging test protocols by the weight loss method. They concluded that the AMACORT CIFD-01 protocol is faster than the fog/dry procedure and corresponds better to a realistic ballast tank environment. However, given the similarity with the fog/dry test acceleration factor and because the fog/dry test demands fewer manipulations, the fog/dry test is a good alternative. The fog/dry test is even at an advantage due to its replicability.

Here, a similar comparison was made for coated and scribed specimens. Application of the AMACORT CIFD-01 protocol causes the most degradation of the coating and the largest formation of visible rust along the scribe, not including blister formation (Table 1).

When blister formation along the scribe is taken into account, the fog/dry protocol causes the most corrosion instead of AMACORT CIFD-01 (Table 2). Immersion testing did not result in blister formation. Given that the AMACORT CIFD-01 test method combines immersion with fog/dry cycles, it exhibited less creep compared to samples exposed solely to the fog/dry testing method.

Additionally, exact measurements of creep demonstrate a large variance of creep spread, which is predominantly present after fog/dry exposure (Figure 3). A one-way ANOVA indicated that the test protocol causes significant differences in the occurrence of creep with blisters ($p = 3.81 \times 10^{-7}$), with a significant difference ($p = 0.012$) between the fog/dry and the AMACORT CIFD-01 treated coupons. Similar differences were noted for creep without blister formation ($p = 2.86 \times 10^{-5}$) with a significant difference between fog/dry and AMACORT CIFD-01 coupons ($p = 0.008$).

Table 1 Rating visible rust creep obtained with the considered accelerated corrosion test protocols

Test protocol	Rating visible rust creep	Standard deviation visible rust creep	Coefficient of variance visible rust creep
AMACORT CIFD-01	8	1.01	0.12
FOG/DRY	9	0.52	0.06
IMMERSION	10	0	0

Table 2 Rating rust creep with blisters obtained with the considered accelerated corrosion test protocols

Test protocol	Rating rust creep with blisters	Standard deviation rust creep with blisters	Coefficient of variance rust creep with blisters
AMACORT CIFD-01	5	0.5	0.10
FOG/DRY	4	1.3	0.34
IMMERSION	10*	0*	0*

* no blisters present



Figure 3 Mean creep results from the considered accelerated corrosion test protocols: the blue series represents visible rust creep, while the orange series represents rust creep with blisters

The fog/dry testing method is visibly more aggressive towards adhesion. It should be stipulated that when the intention of the accelerated corrosion simulation is to represent a ballast tank environment and investigate the behaviour of a coating in such conditions by scribe analysis, the fog/dry test is not an ideal choice. Willemen et al. [5] previously excluded immersion testing as a representative method for simulating accelerated ballast tank corrosion environments; based on this finding, the fog/dry testing procedure can be added. Willemen et al. concluded that for bare steel, the fog/dry test is a true competitor to the AMACORT CIFD-01 test procedure when considering the aging acceleration factor obtained. Examination of the scribe performance of coated steel reveals a clear difference in the outcome, supporting the observation of Quill et al. [15] that the closer the laboratory exposure mirrors the service environment, the more valuable the test data becomes. An important additional observation highlighting the value of the

AMACORT CIFD-01 accelerated corrosion test method is the significantly lower variance observed in the test results when compared to those obtained using the fog/dry method. This reduced variability can be a crucial factor in scientific testing, as it enhances the reliability and reproducibility of the results. Lower variance ensures a more consistent performance evaluation of coatings, providing higher confidence in the conclusions drawn from the data. This makes the AMACORT CIFD-01 method particularly advantageous for applications where precision and repeatability are essential, further solidifying its suitability as a preferred test method for scribe performance analysis of coated steel.

3.2 Scribe performance with salt contamination

Application of salt on the coupon surface has a significant impact on creep formation (Table 3, Figure 4). Blister formation becomes clearly more noticeable at

Table 3 Rust creep ratings whilst varying the salt contamination

Contamination target	Contamination added around (20 ± 3) mg/m ²	Contamination added around (50 ± 8) mg/m ²	Contamination added around (100 ± 15) mg/m ²
Results			
Salt concentration	1 g/l	4 g/l	8 g/l
Salt contamination on coupon	(22.1 ± 1.8) mg/m ²	(55.2 ± 5.2) mg/m ²	(112.5 ± 6.5) mg/m ²
Rating visible rust creep	8	8	8
Standard deviation visible rust creep	0.58	0.5	0
Coefficient of variance visible rust creep	0.08	0.06	0
Rating rust creep with blisters	5	5	3
Standard deviation rust creep with blisters	0.82	0.58	0.58
Coefficient of variance rust creep with blisters	0.16	0.13	0.17

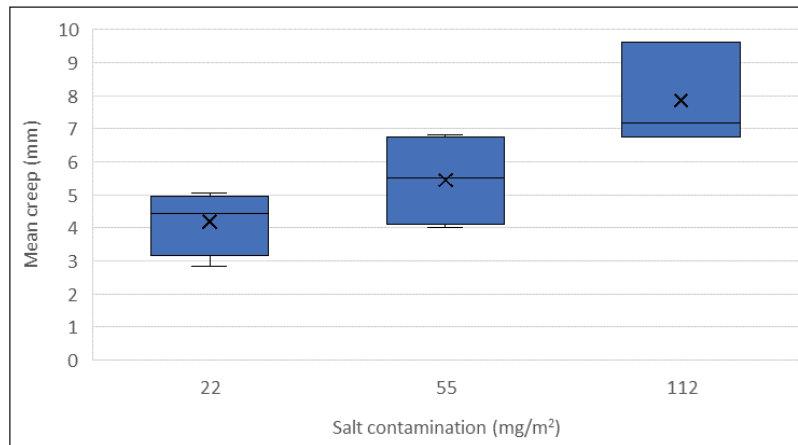


Figure 4 Mean creep rust with blisters whilst varying the salt contamination

higher concentrations, triggering the formation of osmotic blistering. Looking into the more precise scribe measurements, as can be seen in Figure 3, a clear adhesion loss increase is noticed with a salt contamination increase, confirmed by a one-way ANOVA ($p = 0.0193$) test. Pairwise differences show a significant difference between the effect of 22 mg/m² and 112 mg/m² ($p = 0.016$). The PSC₁₅ standard reference of a water-soluble salt limit equivalent to NaCl ≤ 50 mg/m² can therefore be considered as a good standard.

3.3 Scribe performance due to dust contamination

The effect of dust contamination on the scribe performance is given in Table 4. An analysis of the results indicates that the increase in the amount of dust contamination did not result in a statistically significant ef-

fect on visible rust creep in the absence of blister formation (two-way ANOVA, $p = 0.131$ for dust size and $p = 0.892$ for the amount of dust). However, a closer examination of the rating results reveals a notable trend when blister formation is taken into consideration. Specifically, the data suggest that the extent of rust creep increases on average as the grain size of the contaminating particles becomes larger. This observation highlights the relationship between particle size and the overall degradation of coating performance.

The same conclusions can be drawn from the plot of the mean creep measurement values in Figure 5. The adhesion loss increases by about 50% with a grain size increase, considering the added dust contaminations of 110 mg and 330 mg. The outcome of 220 mg dust contamination with a grain size increase remained stable. This results in an average overall adhesion loss of 23%

Table 4 Rust creep rating whilst varying the dust contamination

Results	Contamination target	Contamination added 110 mg dust	Contamination added 220 mg dust	Contamination added 330 mg dust
grain sizes: 50 – 100 microns				
Rating visible rust creep		8	8	8
Standard deviation visible rust creep		0.58	0.5	0.58
Coefficient of variance visible rust creep		0.08	0.06	0.08
Rating rust creep with blisters		5	3	4
Standard deviation rust creep with blisters		0.58	0.96	0.5
Coefficient of variance rust creep with blisters		0.12	0.29	0.12
grain sizes: 100 – 500 microns				
Rating visible rust creep		8	8	8
Standard deviation visible rust creep		0.58	0.5	0.5
Coefficient of variance visible rust creep		0.08	0.06	0.06
Rating rust creep with blisters		3	4	3
Standard deviation rust creep with blisters		0.96	0.58	0.82
Coefficient of variance rust creep with blisters		0.29	0.16	0.27

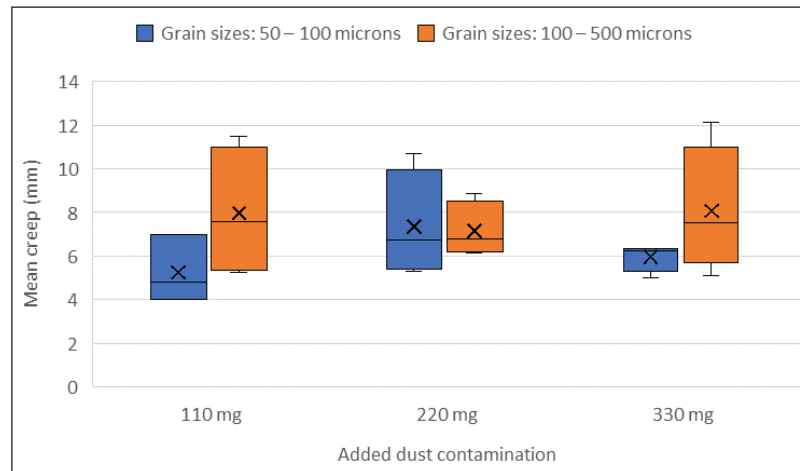


Figure 5 Mean creep rust with blisters assessed for varying levels of dust contamination, with the blue series representing the grain sizes 50 – 100 microns and the orange series showing the grain sizes 100 – 500 microns

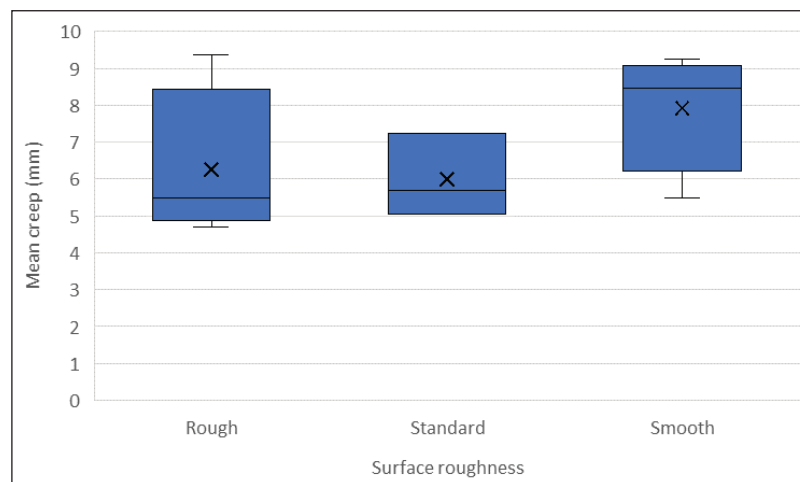


Figure 6 Mean creep rust with blisters whilst varying the surface roughness (rough = Rz around 100 μm , standard = Rz around 60 μm , smooth = Rz around 25 μm) (n = 4).

with a grain size increase from 50 – 100 microns to 100 – 500 microns. Given the large and inconsistent variance observed, the suitability of the fog/dry testing procedure for analysing the impact of dust contamination can be questioned. Amacort C1FD-01 is most likely a better choice to obtain useful data by scribe testing as the variance is clearly less as can be seen in Figure 3. The large variance observed indicates that the rating representation is insufficiently detailed compared with the more precise creep measurement representation provided by the box-and-whisker plot.

3.4 Scribe performance due to a surface roughness non conformity

For the last surface parameter, the surface roughness (Figure 6), the variance in the results is again considerable. No increase in adhesion loss was observed

when the surface roughness was too high, whereas 32% increase in creep was noted when surface roughness was less than prescribed. However, according to a one-way ANOVA, this change in surface roughness was not significantly different ($p = 0.395$).

4 Discussion

The fog/dry test method was employed to analyse the surface parameters. Although unforeseen power interruptions occurred during the test, these interruptions affected all samples equally. Therefore, while the absolute values obtained may have been influenced by these disruptions, the relative differences between samples remain valid. Since the objective of this study is to compare the performance of the samples under identical test conditions rather than to establish absolute performance metrics, the comparative validity of the re-

Table 5 Outliers considered in the different data objectives

Test protocol	Evaluation objective	Number of samples	Number of outliers
AMACORT CIFD-01	Benchmarking scribe	30	0
FOG/DRY	Benchmarking scribe	6	1
IMMERSION	Benchmarking scribe	3	0
FOG/DRY	Salt variance	12	1
FOG/DRY	Dust variance	24	1
FOG/DRY	Surface roughness variance	12	1

sults is maintained. This approach aligns with the principles outlined in ASTM G85 Annex A5 [16], which specifies the Prohesion test method for evaluating the corrosion resistance of coatings. The standard emphasizes that while environmental factors can influence test outcomes, the relative performance differences between coatings under consistent exposure conditions remain a reliable indicator of their durability.

Including benchmarking outcomes in the comparative analysis could have been beneficial for placing the results in a wider context. However, these benchmarking tests were conducted at a different time and under potentially different environmental and operational conditions. Integrating them with the present results would introduce uncontrolled variables, compromising the validity of the comparison. For this reason, benchmarking data were deliberately excluded from the comparative study.

When comparing the behaviour of various coatings, one could question the influence of the scribe shape, keeping in mind reproducibility. Scribing width and depth have been found to show little effect on the test results [17], nor did different scribe tools for narrow (<0.8 mm) and wide (ca. 2 mm) scribes have any notable effect on the extent of corrosion after exposure [18, 19]. Nevertheless, the scribe used in the benchmarking procedure was kept constant, being applied in the same manner by the same hand and with the same tool. The same was valid for the surface parameter study.

In the evaluation of the test protocols for scribed coupons, the number of scribed coupons was diverse. For the immersion phase 3 test specimens were scribed, as not much variance was expected to occur, which was eventually confirmed in Tables 1 and 2. In a study by Hong-Qi Yang et al., investigating the effects of immersion temperature on the performance of a marine epoxy-based organic coating for ballast tanks, low variability was reported in performance metrics such as adhesion strength [20]. For the fog/dry exposure, a total of 6 test specimens were considered. This is consistent with the requirements of the IMO Performance Standard for Protective Coatings [6], which prescribes 5 test panels for simulated ballast tank exposure conditions (cyclic wet/dry) and 2 for condensation chamber testing. The amount was doubled compared to the immersion proto-

col as more variance was expected. For the AMACORT CIFD-01, the amount was considerably higher, namely 30 test specimens, as it was a new in-house test protocol. When calculating the mean creep, outliers observed during testing were excluded from the analysis. These outliers were defined as values that were double the magnitude of the other obtained results. In total, four samples were excluded from the dataset as can be seen in Table 5.

What is striking from Table 5 is that, in the benchmark testing of the scribe, the existing outlier is located within the fog/dry test results. This can be correlated with the fact that the variance is also the greatest in this accelerated corrosion test method, as depicted in Figure 3.

The variance increases considerably when blisters are included in the evaluation of the mean creep, as shown in Table 3. A similar effect is observed for the results of the varied surface parameters. For example, Figure 7 illustrates the surface roughness outcome where the blue series shows the mean creep without considering blisters, while the orange series includes them.

The study, presented at an ISOPE conference by Sakashita et al. [21], examined the corrosion behavior of coated steel substrates in actual water ballast tank environments and reported that “the presence of blisters increases variability in coating performance data, as localized degradation beneath blisters leads to heterogeneous corrosion processes,” which is consistent with our findings. The considerable variability observed in the results can likely be attributed to the inherent characteristics of the scribing process used during testing. When a scribe is made with a scratching tool, the coating is intentionally damaged, resulting in a line of discontinuities where the protective layer is locally destroyed. Along this scribed path, the mechanical action of the tool creates weak points that compromise the integrity of the coating. These damaged regions act as preferential sites for water ingress, enabling moisture to migrate beneath the coating along the scribe. This process facilitates adhesion loss. This variability might underscore the importance of the mechanical properties of the coating in resisting damage due to scribing. Subsequently additional research could be valuable to investigate whether the thickness of the coating, which may provide enhanced resistance to scribing, influences this observed variance. All samples used in

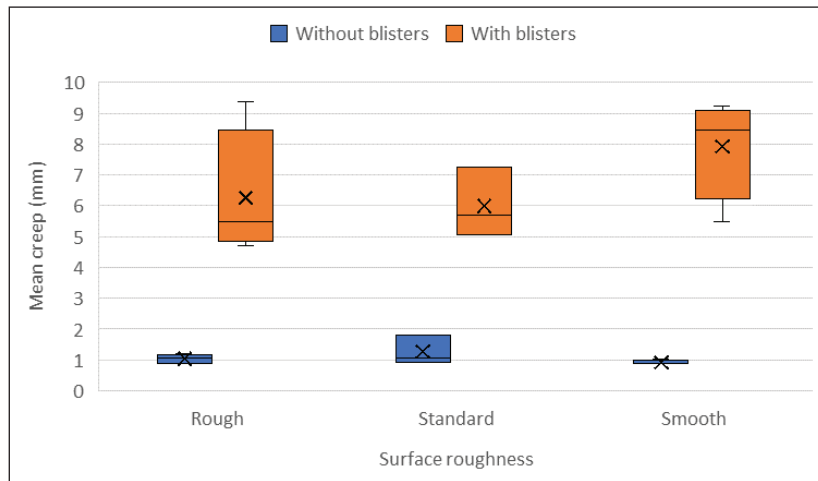


Figure 7 Mean creep versus surface roughness: blue series shows visible rust creep, orange series shows rust creep with blisters

benchmarking creep behavior were coated and scratched in a consistent and standardized manner, ensuring uniformity in the preparation process. These samples were subsequently subjected to identical accelerated corrosion testing protocols. In line with the principles of rigorous scientific research, additional data were collected during the testing process beyond what has been presented thus far in this article. Notably, the coating thickness of the various samples was meticulously recorded before the

scribe was applied and subsequently may provide a more comprehensive understanding of the observed variance. Looking into the 30 samples used in the AMACORT CIFD-01 accelerated corrosion testing, a 0.21 Pearson correlation score was noted between the mean creep after testing and the recorded paint thickness values before applying the scribe. Looking into the 6 samples used in the fog/dry accelerated corrosion test, the Pearson correlation score increases to 0.45.

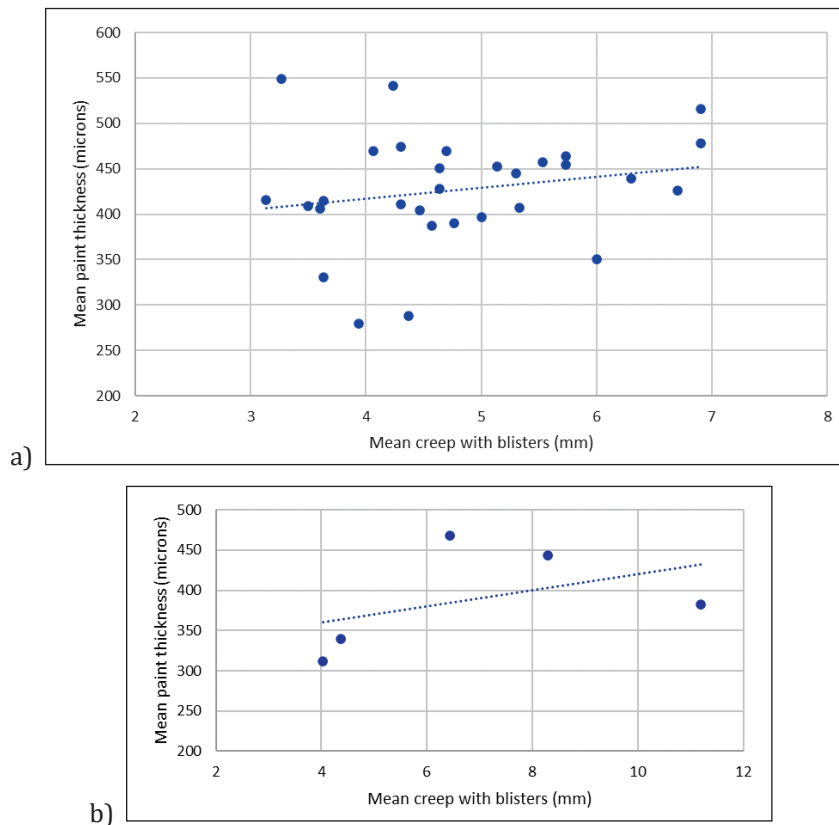


Figure 8 a) Shows the correlation of the mean creep with the paint thickness samples AMACORT CIFD-01
 b) Shows the correlation mean creep with paint thickness samples fog/dry

The Pearson correlation score of 0.21 indicates a very weak positive linear relationship between the mean creep and the paint thickness (Figure 8). This value suggests that there is minimal to no meaningful correlation between the two variables, as the strength of the relationship is negligible. Other models did not perform better, and in fact, hardly differed from the linear result (data not shown). Consequently, a substantial portion of the variability in the mean creep cannot be attributed to changes in the paint thickness. A Pearson correlation score of 0.45 is an increase but still represents a low to a weak correlation. This finding indicates that the fog/dry test procedure exhibits inherent vulnerabilities, leading to significant variance in test outcomes that can be attributed to the test method itself. This variability makes the fog/dry test less suitable for applications where precise and consistent performance evaluation is essential.

A pragmatic approach aligned with on-board practices was adopted, and additional scientific analyses were not conducted such as SEM-EDX analyses of rust. However, further exploration of this topic would be highly engaging and could provide valuable insights. In future research on accelerated corrosion testing, it would also be beneficial to incorporate open circuit corrosion potential measurements.

5 Conclusion

While the fog/dry test effectively accelerates corrosion for bare steel, it is not ideal for representing a ballast tank environment when evaluating coated steel through scribe analysis. This reinforces the assertion by Quill et al. [15] that laboratory tests are most valuable when closely mimicking the service environment. Thus, the AMACORT CIFD-01 test procedure is the most suitable method for evaluating scribe performance of coated steel when representing a ballast tank environment. However, the fog/dry testing method is visibly highly aggressive towards adhesion, making it at first sight an excellent tool for comparative scribed analyses. This research also highlights that the variability inherent in fog/dry accelerated corrosion testing is notably significant, posing challenges to achieving precise and detailed test outcomes. Consequently, the AMACORT CIFD-01 method demonstrates advantages in contexts where precision and repeatability are critical. This establishes its suitability as a preferred testing methodology for the scribe performance analysis of coated steel.

When evaluating coating performance in relation to surface cleanliness and surface roughness, several key observations can be made. First, there is a clear increase in mean creep with rising levels of salt contamination. This increase becomes statistically significant when contamination exceeds the limits defined by the PSPC₁₅ standard.

Regarding dust contamination, the grain size of the dust particles plays a role in affecting mean creep performance. Larger dust particles are particularly detrimental, as they disrupt the coating's integrity and contribute to adhesion loss. Nevertheless, the effect is not considered significant.

Lastly, surface roughness also influences coating performance, though the effects vary based on deviation from the standard. Deviations toward a rougher surface do not impact adhesion loss. However, a smoother-than-standard surface has a negative effect on coating performance, likely due to insufficient mechanical interlocking between the coating and the substrate. But then again, the effect is not considered significant.

These findings underscore the importance of selecting appropriate test methods and maintaining adherence to surface cleanliness and roughness standards, in particular salt contamination, to ensure optimal coating performance and adhesion durability.

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