Konversi Energi dan Manufaktur

P-ISSN : 2339-2029
E-ISSN : 2622-5565

Jurnal Konversi Energi dan Manufaktur
Volume 11 Number 2 – July 2026 Page 152-169
Website : http://journal.unj.ac.id/unj/index.php/jkem
DOI: https://doi.org/10.21009/JKEM.11.2.6

Protective Coating Performance on Industrial Components During Shutdown Maintenance

Toni Okviyanto[1], Agus Subeno[2*], Dibyo Setiawan[3], Fauzi Widiawati[3], Edward Simanjuntak[3], Otong Jaelani[4]

[1] *Department of Mechanical Engineering, Sriwijaya State Polytechnic, South Sumatra, 30128, Indonesia.*
[2] *Department of Mechanical Engineering, Al-Kamal Institute of Science and Technology, Jakarta, 11520, Indonesia.*
[3] *Department of Mechanical Engineering, Bandung State Polytechnic, West Java, 40559, Indonesia.*
[4] *Department of Mechanical Engineering, Mandala Technology College, West Java, 40284, Indonesia.*
* Corresponding Author. E-mail : agus.subeno@ista.ac.id

Article information - : Received : 07-05-2026; Revised : 12-06-2026; Accepted : 25-06-2026

Abstract

Corrosion protection is a critical aspect of industrial maintenance because coating quality directly influences equipment durability, operational reliability, and long-term maintenance efficiency. However, coating assessments in industrial practice often focus on compliance with thickness specifications without comprehensively evaluating the relationship between surface preparation quality, environmental conditions, coating thickness, and final coating performance under actual shutdown maintenance conditions. This study aimed to evaluate the effectiveness of the coating process during total plant shutdown (TPS) painting work on four industrial components: the sole plate sag mill, cover motor ball mill, base frame motor bubble crusher, and OHC girder. A field-based coating performance assessment was conducted using final painting reports, visual inspection records, environmental condition monitoring, surface preparation evaluation, and dry film thickness (DFT) measurements. Surface preparation was carried out using ST 3/SSPC-SP 3 mechanical cleaning, while coating performance was evaluated against the specified DFT requirements. The results showed that all inspected components satisfied the acceptance criteria, with primer DFT values exceeding 150 μm and final DFT values exceeding the minimum system requirement of 225 μm. Final coating thickness increased by 263–347 μm compared to the existing condition, indicating the formation of a protective coating layer. Nevertheless, noticeable thickness variations among measurement locations suggest opportunities for improving application consistency and process control. These findings demonstrate that the applied coating system met the specified performance requirements and provided effective corrosion protection under field conditions, while further optimization of coating application practices is required to achieve more uniform and efficient coating performance.

Keywords: corrosion protection; dry film thickness; surface preparation; industrial maintenance; coating evaluation.

1. Introduction

Corrosion is one of the most important material-related challenges in industrial asset management because it directly affects equipment reliability, operational safety, maintenance cost efficiency, and the service life of structures. Globally, the cost of corrosion is estimated to reach approximately US$ 2.5 trillion, or about 3.4% of the world's gross domestic product (GDP). Therefore, corrosion control is no longer viewed merely as a technical issue but also as an economic and risk-management concern [1]-[3]. In steel-based industries, particularly in the mining, heavy manufacturing, energy, and infrastructure sectors, corrosion accelerates the degradation of component integrity, increases the frequency of operational shutdowns, and necessitates repeated inspections and repairs [4], [5]. Therefore, selecting an appropriate surface protection system, carrying out coating work in accordance with established procedures, and verifying the quality of the applied coating are critical factors in ensuring the success of an asset integrity management strategy [6]-[8].

Organic coating systems remain the most widely used corrosion protection method for metallic materials because they are relatively flexible, cost-effective, easy to apply, and can be tailored to specific service environments [9], [10]. The review study emphasizes that organic coatings remain the most commonly applied

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DOI: https://doi.org/10.21009/JKEM.11.2.6

corrosion protection method for metallic materials, particularly in the transportation and infrastructure sectors. However, coating failure mechanisms cannot yet be predicted in a simple, fully reliable manner [11], [12]. This finding indicates that coating performance is not determined solely by the type of paint used, but also by the quality of the interface between the substrate and the coating layer, the ability of the coating to resist the penetration of water and aggressive ions, and the stability of the coating system throughout its service life. In other words, coating performance in the field results from complex interactions among coating system design, initial surface condition, application method, coating thickness, and exposure to the operating environment [13]-[15].

The quality of surface preparation is a critical factor in determining the success of a painting system, as a protective coating can only perform optimally when applied to a clean, stable surface with an appropriate roughness profile. A study demonstrated that surface preparation methods significantly affect coating performance. They compared several steel surface preparation methods before painting and found that the resulting surface characteristics contributed to the coating's anticorrosion resistance [16], [17]. The article also explains that the relationship among surface roughness, adhesion, and corrosion resistance has not always been consistent in the literature; therefore, case-specific evaluation under field conditions remains necessary. Thus, surface preparation should not be treated merely as an administrative preliminary step, but rather as a surface engineering stage that determines the quality of bonding between the primer and subsequent coating layers [18]-[20].

Dry film thickness (DFT) also plays an important role because it is associated with the coating's ability to form a barrier against moisture, oxygen, and other corrosive substances that may reach the steel substrate. A study on repair coatings for offshore wind structures showed that when dry blast cleaning is not feasible, increasing the coating thickness may be recommended to maximize corrosion protection [21]. On the other hand, various international studies also emphasize that zinc-rich primers and epoxy-based systems remain the primary choices for heavy-duty applications because they provide a combination of barrier protection and cathodic protection. Therefore, DFT is not simply a quality control value, but also a parameter that directly influences the functional performance of the coating system. Insufficient thickness may accelerate the permeation of corrosive media, whereas uncontrolled excessive thickness may also lead to application defects, cracking, or inter coat adhesion problems [22].

Aggressive operating environments make coating evaluation increasingly urgent, particularly for assets operating in open areas, humid atmospheres, salt aerosol exposure, process water splashing, abrasive dust, and temperature fluctuations. A study explains that steel structures exposed to aggressive environments require durable corrosion mitigation strategies. In atmospheric zones, epoxy-based coating systems combined with polyurethane top coats are commonly used. The article also emphasizes that selecting a protection strategy is not straightforward, as it must consider the design life, maintenance costs, testing methods, and the system's suitability for the relevant corrosivity zone. Although the offshore wind context is not identical to all industrial facilities, the underlying principle remains relevant: the more severe the environmental exposure, the more critical the quality of coating design and application becomes in ensuring the service life of the asset [23]-[26].

The success of painting activities during shutdown periods in industrial practice is largely determined by procedural discipline, consistent inspection, and complete quality documentation. A shutdown or total plant shutdown (TPS) period provides an optimal opportunity to perform inspection, cleaning, repair, and recoating activities without disrupting main operations. However, it also presents significant challenges, including high time pressure, limited access to work, variability in existing surface conditions, and the need for coordination across multiple activities, such as scaffolding, blasting, and mechanical maintenance. These conditions require strict quality control to ensure the coating continues to meet technical specifications. In this regard, research by Schoenholz et al. [27] showed that field testing of coating resistance and repair materials plays a crucial role in improving the reliability of protective system selection. Some repair materials have even been shown to tolerate less-than-ideal surface preparation quality [27]. These findings emphasize that direct evaluation of coating performance under field conditions remains necessary, since laboratory test results do not always represent the complexity of actual conditions in industrial maintenance [28]-[31].

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Various studies have highlighted the importance of analysing the relationship between surface treatment, coating systems, and corrosion rate in steel materials. Qusayyi et al. [32] reported that coating was effective in inhibiting corrosion in ST 60 steel, while variations in salinity and sandblasting duration affected surface roughness as well as the corrosion rate [33]. Wibowo and Ghofur [34] demonstrated that the level of surface cleanliness prior to coating influenced the adhesive strength and corrosion performance of epoxy coatings on A36 steel. In that study, a certain cleanliness level produced the highest adhesion, whereas another resulted in the lowest corrosion rate. Meanwhile, Santosa et al. [35] showed that coating methods such as hot-dip galvanizing were able to significantly reduce the corrosion rate of AISI 1020 steel. These three findings consistently indicate that corrosion protection is not only a matter of whether a coating is applied, but also depends on the quality of the process and the application parameters [36]-[39].

However, a significant research gap remains in the limited integration of field quality control/quality assurance (QA/QC) documentation from shutdown maintenance activities into a systematic framework for evaluating coating performance on actual industrial equipment. This limitation is important because coating effectiveness in practice is influenced not only by material properties but also by field conditions, surface preparation quality, application practices, and inspection outcomes, which are not often fully represented in laboratory-based studies. To address this gap, the present study utilizes actual field inspection and painting documentation to evaluate the relationships among initial surface condition, surface preparation method, coating system characteristics, DFT, and final visual inspection results. By linking these practical quality control records with coating performance assessment, the study provides a more realistic basis for evaluating coating effectiveness and supporting future maintenance planning and inspection improvement strategies [40], [41].

In addition, recent international studies show that coating evaluation has moved toward a more integrative approach. This approach does not only assess coating condition immediately after application but also predicts coating degradation by integrating environmental factors, physical coating properties, and damage development over time. High relative humidity, specific temperature conditions, and nighttime exposure can accelerate the degradation of organic coatings in tropical marine atmospheres. Other studies also emphasize that zinc-rich primers remain an important heavy-duty anticorrosive option because they provide cathodic protection and support the formation of corrosion products that strengthen the coating barrier. Therefore, the evaluation of painting work in industrial facilities should not stop at administrative compliance with specifications. It should address a more substantive question: to what extent can the achieved application quality support service life and reduce the risk of further corrosion [42]-[44].

This study evaluates the quality of painting work during TPS as an important step in connecting practical industrial needs with a scientific approach to coating evaluation. The focus of this study is to assess the conformity of surface preparation, primer application, top coat application, and the achieved DFT with the corrosion protection objectives for steel components. The results of this study can provide a basis for recommendations to improve maintenance procedures, enhance QA/QC inspection quality, and determine more efficient asset maintenance priorities. The use of field data from painting reports during TPS supports the development of a more systematic evaluation of coating quality on industrial equipment. This study provides both academic contributions and practical benefits for managing the reliability of industrial facilities.

2. Experimental Methods

The research method employed in this study is a field case study with a descriptive-evaluative approach to analyze the effectiveness of coating systems applied to metal surfaces during shutdown painting activities. The study focuses on evaluating each stage of the coating process, including specification determination, surface condition inspection, surface preparation, primer application, coating thickness measurement, top coat application, visual inspection, and final analysis. This approach is selected because it provides a comprehensive assessment of the conformity between coating procedures and the applicable technical standards in field operations.

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Figure 1. Condition of the plant to be coated

The research is conducted using technical work documents, coating standards, scientific references, and field inspection data related to the coating process shown in Figure 1. The analysis aims to evaluate whether the applied coating system meets the required level of protection for metal surfaces operating in aggressive industrial environments. The primary parameters analyzed include initial surface condition, surface preparation method, coating system type, DFT, and final visual quality.

2.1. Research Stages

The initial stage of the research begins with a literature review to establish a theoretical foundation related to corrosion, metal coating systems, surface preparation methods, and coating quality parameters. The references include national and international journals, technical standards, and relevant industrial guidelines. This stage enables the development of an evaluation framework for assessing coating system performance.

In addition, specifications are determined, including the identification of the coating system type, coating sequence, application methods, and quality control parameters. This stage is essential because it establishes the baseline criteria for evaluating whether the coating process and its results comply with the technical requirements.

2.2. Surface Condition Inspection

After defining the specifications, the next stage is to inspect the metal surface condition before coating application. This inspection intents to identify the initial substrate condition, including the presence of rust, peeling coatings, surface contaminants, dust, oil, or other defects that may affect coating adhesion. The inspection is conducted visually and supported by available technical inspection records.

This stage is critical because coating performance depends heavily on the initial surface condition. Surfaces contaminated with active corrosion or impurities may lead to coating failure. Therefore, the inspection results are used to determine the appropriate level of cleaning and surface preparation method. The initial inspection is presented in Figure 2.

Figure 2. The initial inspection

2.3. Surface Preparation

Surface preparation is performed to ensure the metal substrate is in optimal condition before coating application, in accordance with verified technical parameters and standards. The primary method used is power

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tool cleaning in accordance with ST 3 (ISO 8501-1) [45], equivalent to SSPC-SP 3 [46], which involves mechanical cleaning using powered tools to remove loose rust, deteriorated coatings, and surface contaminants without fully exposing the base metal. This process is complemented by hand-tool cleaning methods, such as scraping, wire brushing, and sandpapering in localized areas, to ensure thorough contaminant removal. The evaluated parameters include cleaning methods, surface cleanliness level, and substrate readiness for coating application.

Evaluation is conducted through visual inspection, comparing actual conditions with ST 3/SSPC-SP 3 criteria, which require surfaces to be free of oil, grease, dust, loose rust, and poorly adhered coatings, while allowing well-adhered existing coatings to remain. Prior to coating application, the surfaces were inspected for contaminants and coating degradation. The contaminants identified during inspection included dust, dirt, loose rust, iron oxide, deteriorated coating residues, and other foreign materials that could interfere with coating adhesion. Surface preparation was performed using a combination of hand tool cleaning, power tool cleaning, scraping, and sandpapering in accordance with SSPC-SP 3 requirements. Areas showing loose rust and oxide formation were mechanically cleaned until a sound substrate and firmly adhered coating surface were obtained [47]-[49]. The power tool cleaning process is shown in Figure 3.

We defined the acceptance criteria at this stage so that the surface is considered satisfactory if it is free of contaminants that may interfere with coating adhesion, showing no active corrosion and an inherent surface roughness from mechanical cleaning. The mechanical cleaning will support mechanical bonding between the substrate and the coating system. Analytically, the application of the ST 3/SSPC-SP 3 method indicates that the coating work falls within the maintenance or recoating category, where existing coatings that remain well-adhered are retained as part of the new coating system. This approach is particularly relevant under shutdown conditions. They are typically constrained by limited time and accessibility, while requiring consistent quality control. Therefore, the success of surface preparation is not solely determined by compliance with the specified standards, but also by the consistency of execution in the field. In this study, this consistency is validated through correlations between surface cleanliness results, achieved DFT values, and the coating's visual quality in subsequent stages [50].

Figure 3. Power tool cleaning

2.4. Primer Coat Application

Once the surface is confirmed to meet the required readiness criteria, the process proceeds to the application of the primer coat, and the initial stage in forming the coating system. The primer provides corrosion protection and enhances inter coat adhesion. In this study, primer application is not only described qualitatively but also analysed using measurable technical parameters, including application methods, coating uniformity, and primer DFT. The application methods employed include brush, roller, or spray, selected based on surface geometry and field accessibility.

The primer coat used in this study was a high-build epoxy mastic coating. Prior to application, all coating materials were verified against manufacturer documentation, including batch identification, shelf-life status, expiration records, and storage conditions. The materials were confirmed to remain within the manufacturer's

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recommended storage period and were free from any signs of deterioration. Before application, each coating component was thoroughly mixed until a homogeneous consistency was achieved in accordance with the manufacturer's recommendations. Coating viscosity was controlled according to the manufacturer's technical specifications and adjusted when necessary, using the recommended thinner to ensure proper atomization, film formation, and application quality.

The coating materials were applied using brush, roller, or spray methods depending on surface geometry, accessibility, and field conditions. During spray application, the spray gun was maintained at a distance of approximately 20–25 cm (8–10 inches) from the substrate surface and oriented at an angle of approximately 90° to the surface. This application technique promoted uniform coating deposition and film formation, minimized coating porosity and application defects, improved coating continuity and inter coat adhesion, and enhanced the overall quality of the coating system. Maintaining the recommended spray distance and orientation also contributed to improving thickness uniformity and long-term corrosion protection performance.

The interval between primer and top coat application followed the recoating schedule specified by the coating manufacturer to ensure adequate inter coat adhesion and curing performance. The mixed coating material was applied within the manufacturer's recommended pot life to prevent viscosity increase and application defects. DFT measurements, handling, and subsequent coating operations were performed only after the coating had reached the required drying and curing conditions. Based on the manufacturer's technical data sheet, the coating was allowed to achieve appropriate surface-dry, hard-dry, and handling conditions before inspection and overcoating to ensure accurate thickness measurements, proper film integrity, and optimal long-term coating performance.

Evaluation is conducted by verifying compliance with established technical procedures and by directly measuring coating thickness at several representative points using a dry-film thickness gauge. The acceptance criteria at this stage specify that the primer layer is considered satisfactory if the minimum thickness is≥150 µm, is in accordance with the coating system specification, and exhibits uniform distribution without indications of initial application defects.

Analytically, the primer layer plays a critical role in determining the overall performance of the coating system, as it serves as the primary interface between the substrate and the final coating layers. DFT measurement results exceeding the minimum requirement indicate that, quantitatively, the primer fulfils its initial protective function. However, variations in thickness across different objects suggest inconsistencies in field application control. This condition indicates that the success of the primer stage is not solely determined by meeting minimum specifications, but also by maintaining application consistency to prevent coating irregularities. Therefore, the evaluation at this stage does not only assess compliance with technical standards but also interprets the quality of the application as an integral component of the overall protective coating system. The primer coat application is shown in Figure 4.

Figure 4. The primer coat application

2.5. Primer DFT Inspection

After the primer coat application is accomplished, a DFT inspection is carried out as part of a measurable and standardized quality verification process. The primary parameter analysed is the coating thickness in micrometres (µm), measured using a DFT gauge at several representative points to ensure data validity and consistency. The

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evaluation method involves comparing the measured values with the specified technical requirement, which is a minimum of ≥150 μm for the primer layer. In addition, the assessment also considers the uniformity of thickness distribution across the surface, as excessive variation may indicate a lack of control in the application process. Consequently, primer DFT inspection functions not only as a quantitative measurement but also as an indicator of application quality in the field.

The acceptance criteria at this stage require that the primer layer is considered satisfactory if the measured thickness meets or exceeds the minimum specification and does not exhibit extreme deviations between measurement points. If the measured thickness does not meet the requirement, corrective actions such as recoating or spot repair are implemented until the specified value is achieved. Conversely, if the inspection results comply with the criteria, the process can proceed to the top coat application stage. Analytically, this stage serves as a critical initial quality control checkpoint, as it determines whether the coating system has established an adequate protective foundation prior to the application of the final layer, thereby directly influencing the overall effectiveness of the coating system. The DFT inspection was conducted only after the primer coating had reached an appropriate drying and handling condition. This ensured that the measured thickness represented the actual cured coating layer and minimized potential measurement errors associated with premature inspection.

2.6. Top Coat Application

The next stage is the application of the top coat as the final layer in the coating system, which is carried out after the primer layer has met the acceptance criteria. In this study, the top coat application is not only described in general terms but also analysed based on technical parameters, including application methods, coating uniformity, and its contribution to the total coating thickness.

The top coat material used in this study was the aliphatic polyurethane coating. Prior to application, the coating material was mixed according to the manufacturer's procedure to obtain a homogeneous composition. The interval between primer and top coat application followed the recoating schedule recommended by the coating manufacturer to ensure adequate inter coat adhesion and curing performance. The application methods may include brush, roller, or spray, depending on field conditions, surface geometry, and accessibility. For spray application, the spray gun was maintained at a distance of approximately 20–25 cm (≈ 8–10 inches) from the substrate surface and oriented at an angle of approximately 90° to the coated surface. This application technique was intended to achieve more uniform coating deposition and film formation, minimize coating defects such as porosity, overspray, and uneven thickness distribution, and improve coating continuity. Maintaining the correct spray distance and orientation also contributes to stronger interlayer adhesion, reduced coating porosity, enhanced coating integrity, and improved long-term durability of the protective coating system. The evaluation is conducted by verifying compliance with established technical procedures and ensuring that the application is performed sequentially over a primer layer that meets the required standards. In addition, observations are made to assess whether the coating is applied uniformly and is capable of adequately covering the surface.

The acceptance criteria at this stage are determined based on the achievement of both protective and aesthetic functions. The top coat must enhance resistance to moisture, chemicals, ultraviolet radiation, and abrasion, while also producing a uniform surface appearance. Analytically, the top coat plays a critical role as the outermost layer that directly interacts with the operating environment; thus, the quality of its application significantly influences the service life of the overall coating system. Nonconformities at this stage, such as uneven coating or application defects, may become the initiation point of coating degradation even if the primer layer has met the required specifications. Accordingly, the evaluation of the top coat stage in this study focuses not only on procedural compliance but also on the integrity of the final layer as part of a comprehensive protective system. The top coat application is shown in Figure 5.

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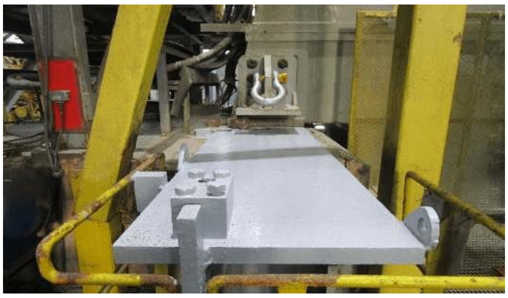

Figure 5. The top coat application

2.7. Top Coat DFT Inspection

After the top coat application, a DFT inspection is conducted as the final verification of the coating system's quantitative parameters. The parameters analysed include the final coating thickness (total DFT) in micrometres (μm), measured at several representative points using a DFT gauge to ensure accurate, consistent results. The evaluation method involves direct measurement and comparison with the technical specifications of the coating system, which requires a minimum thickness of ≥225 μm, consisting of a 150 μm primer and a 75 μm top coat. In addition, the evaluation also considers the uniformity of thickness distribution across measurement points, as significant variation may indicate a lack of control in the application process. Therefore, top coat DFT inspection serves not only as a verification of thickness values but also as an indicator of the overall quality of the coating process. The final DFT inspection was performed after the coating system had completed the required drying and curing stages. Visual inspection was conducted simultaneously to identify potential coating defects such as runs, sags, pinholes, blistering, or incomplete coverage that could affect the protective performance of the coating system.

The acceptance criteria at this stage require that the total DFT meets or exceeds the minimum specified value and does not exhibit extreme deviations that could affect protective performance. If the measurement results indicate nonconformity, corrective actions such as touch-up, spot repair, or recoating in specific areas are carried out until the required thickness is achieved. Conversely, if the inspection results meet the criteria, the coating work can be technically declared complete and proceed to the visual evaluation and final analysis stages. Analytically, this stage represents a critical final quality control checkpoint, as it determines whether the applied coating system can provide adequate protection under operating environmental conditions.

2.8. Visual Inspection

The next stage involves a visual inspection of the final coating as a non-destructive quality verification method to assess the integrity of the coating layer. The observed parameters include surface defects such as sagging, blistering, orange peel, pinholes, and cracking, as well as color inconsistency and uneven coating distribution. The evaluation is conducted through visual inspection based on photographic documentation and field inspection records, by comparing actual conditions with acceptable coating quality criteria. The acceptance criteria at this stage specify that the coating is considered satisfactory if no dominant defects are found that could reduce its protective function or indicate early failure. Therefore, visual inspection serves not merely as a complementary assessment but also as a critical validation step, since a coating that meets DFT specifications does not necessarily guarantee good physical application quality.

Environmental conditions were monitored throughout the coating process using daily ambient condition records as part of the quality control procedure to evaluate their influence on coating performance. The monitored parameters included steel surface temperature (ST), ambient temperature or dry bulb temperature (DBT), relative humidity (RH), and dew point temperature (DPT), as well as potential contaminants such as dust and moisture that could affect coating film formation and curing. Measurements were performed on site using calibrated thermohydrometers and surface thermometers at regular intervals during the painting process, with measurement points located as close as possible to the coated surfaces to accurately represent actual application conditions. All data were systematically recorded in daily inspection sheets and evaluated against coating

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P-ISSN : 2339-2029
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DOI: https://doi.org/10.21009/JKEM.11.2.6

application requirements. Coating application was permitted only when the RH remained within acceptable limits and the ST was at least 3°C above the DPT to prevent condensation and ensure proper coating adhesion and curing.

The collected data were subsequently processed and visualized in an ambient chart to illustrate trends in environmental conditions over time and support technical evaluation of the suitability of coating application conditions. Analytically, uncontrolled environmental conditions can cause coating defects even when application procedures are followed correctly. It indicates that coating quality is determined by both technical parameters such as DFT and the appropriateness of the environmental conditions during application. The integration of visual inspection and environmental condition evaluation in this study provides a more comprehensive approach to assessing the overall effectiveness of the coating system.

2.9. Analysis and Discussion

The final stage of this study involves the analysis and discussion of all evaluation results, conducted systematically based on measurable parameters. At this stage, the parameters analysed include the conformity of the coating process with technical specifications, the effectiveness of the surface preparation method, the quality of primer and top coat applications, as well as the results of coating thickness (DFT) inspections and visual evaluations. The analysis method employed is a descriptive-analytical approach, in which measurement data and field findings are interpreted through comparison with applicable technical standards and references from previous studies. This approach allows each parameter to be evaluated individually and interrelationship in contributing to the overall performance of the coating system.

The evaluation criteria in this stage are based on meeting minimum specifications, considering consistency across different objects, conformity of the process with established procedures, and the technical implications for coating protection performance. Systematically, the discussion is directed toward identifying the effectiveness level of the coating system in enhancing metal surface protection, while also revealing potential process deviations such as thickness variations or application irregularities that may affect coating service life. Hence, the analysis results are descriptive and comprehensive technical interpretation of the field data. All measurement results, visual documentation, and comparisons with standards and literature are presented in the analysis and discussion section, ensuring that the methodology section remains a systematic and transparent procedural framework.

3. Results and Discussion

3.1. Analysis of Initial Surface Condition Inspection

The initial surface condition inspection was evaluated based on several parameters, specifically the existing (initial DFT), the visual condition of the old coating, and indications of degradation such as corrosion and surface non-uniformity. The evaluation method was carried out through analysis of the existing DFT data recorded in the final painting report and interpretation of field visual documentation.

In this study, the validation basis for the acceptance criteria at the initial stage was determined by assessing the suitability of surface for recoating. The surface was considered acceptable if the old coating still had partial adhesion and could be prepared using mechanical methods without requiring total removal down to the base metal. The initial inspection results are presented in Table 1.

Table 1. DFT measurement results

Object	Existing DFT (μm)	Actual primer DFT (μm)	Actual top coat/final DFT (μm)
Sole plate sag mill	32	186	295
Cover motor ball mill	480	547	730
Base frame motor Bubble crusher	460	632	807
OHC girder	476	668	765

Konversi Energi dan Manufaktur

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Table 1 shows there are significant differences in the existing DFT values among the objects. These differences directly reflect the degradation level of the old coating and the initial protection condition of each component. The sole plate of the sag mill had the lowest existing DFT value, namely 32 µm. This indicates that the previous protective coating had experienced a significant loss of function and was no longer able to provide optimal corrosion protection. In contrast, the cover motor ball mill, base frame motor bubble crusher, and OHC girder still had relatively high existing coating thicknesses, each above 450 µm. This indicates that the previous coating system was still present and potentially contributed to surface protection, although local degradation may have occurred. These differences show that the coating damage was not uniform. Consequently, the initial DFT condition became an important indicator in determining the required follow-up treatment for each object.

From a descriptive and analytical perspective, the variation in the initial surface condition had a direct implication for the recoating strategy and the validation of coating process suitability [50]-[52]. The sole plate of the sag mill tended to require a rebuilding system approach because its low initial thickness showed that the old coating was no longer effective. Visual indications of corrosion and surface irregularity also supported this condition. Meanwhile, the cover motor ball mill and OHC girder were more appropriately categorized under maintenance coating, in which recoating was intended to reinforce the existing coating system. The base frame motor bubble crusher was in a transitional condition that required more intensive surface preparation, although quantitatively, it still had a relatively sufficient coating thickness. In terms of acceptance criteria validation, all objects were declared suitable for recoating because mechanical cleaning could still be performed without total removal down to the base metal. The substrate remained within the acceptable process category; thus, this analysis explains the initial condition numerically and provides a technical basis for determining the appropriate coating approach and serves as a reference for evaluating coating effectiveness in the next stage.

3.2. Analysis of Surface Preparation

The surface preparation evaluation was carried out based on several parameters, including the cleaning method, the degree of surface cleanliness, and the conformity of the work implementation with technical standards. Based on the final painting report, the main method used was power tool cleaning according to ST 3 standard in ISO 8501-1 [53], which is equivalent to SSPC-SP 3 [46]. This method was applied to corroded areas and areas with coating damage. This method aimed to remove loose rust, non-adherent paint layers, and surface contaminants without completely exposing the entire surface down to the base metal [49]. Additional methods were also applied, including hand tool cleaning, hard scraping on damaged coating areas, and sandpapering as part of local cleaning or spot treatment [54].

The evaluation was conducted through verification of field documentation and comparison with the ST 3/SSPC-SP 3 standard criteria. Based on these criteria, the surface must be free from oil, grease, dust, loose rust, and other contaminants, while only the old coating with good adhesion may remain [55]-[57]. The acceptance criterion at this stage was established by determining that the surface was acceptable if it met the required cleanliness level and had a condition that allowed adequate mechanical bonding between the substrate and the coating layer [45]. The surface preparation parameters are shown in Table 2.

Table 2. The surface preparation parameters

Aspect	Description
Main method	Power tool cleaning st 3.0 / SSPC-SP 3 on corroded areas
Additional cleaning	Hard scraping of damaged paint, hand tool cleaning, and sandpapering
Surface requirements	Free from water, oil, grease, dust, and contaminants
Technical objective	To prepare the surface so that it is suitable for primer and top coat application

Table 2 shows that the surface preparation process combined mechanical cleaning and localized treatment methods. This indicates that the preparation method was adjusted to the actual condition of each work area. The ST 3/SSPC-SP 3 method was technically suitable for the maintenance coating category. In this method, the old coating with good adhesion was retained, while only degraded areas were cleaned. This approach was relevant

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Website : http://journal.unj.ac.id/unj/index.php/jkem
P-ISSN : 2339-2029
E-ISSN : 2622-5565
DOI: https://doi.org/10.21009/JKEM.11.2.6

to field conditions during the shutdown period, where time and access were limited. It also did not require surface exposure to a near-white metal condition as required in abrasive blasting. Validation of the acceptance criteria showed that all objects met the requirements. No dominant contaminants were found that could interfere with coating adhesion. In addition, the final results showed an increase in DFT values and visual improvement toward a more uniform coating layer. The use of several cleaning methods indicates that the surface preparation process was not fully uniform across all areas. Therefore, the quality of the final result depended strongly on the consistency of field implementation. Thus, although the methods used were technically adequate and complied with the required standards, process control remained an important factor influencing the overall effectiveness of the coating results.

3.3. Environmental Condition Analysis

Environmental condition control during the coating application process is a critical factor in ensuring the success of the coating system. Parameters such as ST, DPT, RH, and DBT directly affect adhesion mechanisms, film formation, and coating curing. Inadequate environmental conditions, particularly when the difference between ST and DPT does not meet the minimum requirement or when humidity levels are excessively high, can cause condensation on the steel surface, potentially leading to defects such as blistering, poor adhesion, and premature coating failure [42], [58]. Therefore, ambient conditions are regularly monitored throughout the painting process to ensure that all parameters remain within the permissible range as defined by applicable technical standards. The measurement data are then presented in an ambient chart (Figure 6) to illustrate trends in environmental conditions over time and to serve as a basis for evaluating the overall feasibility of the coating application process.

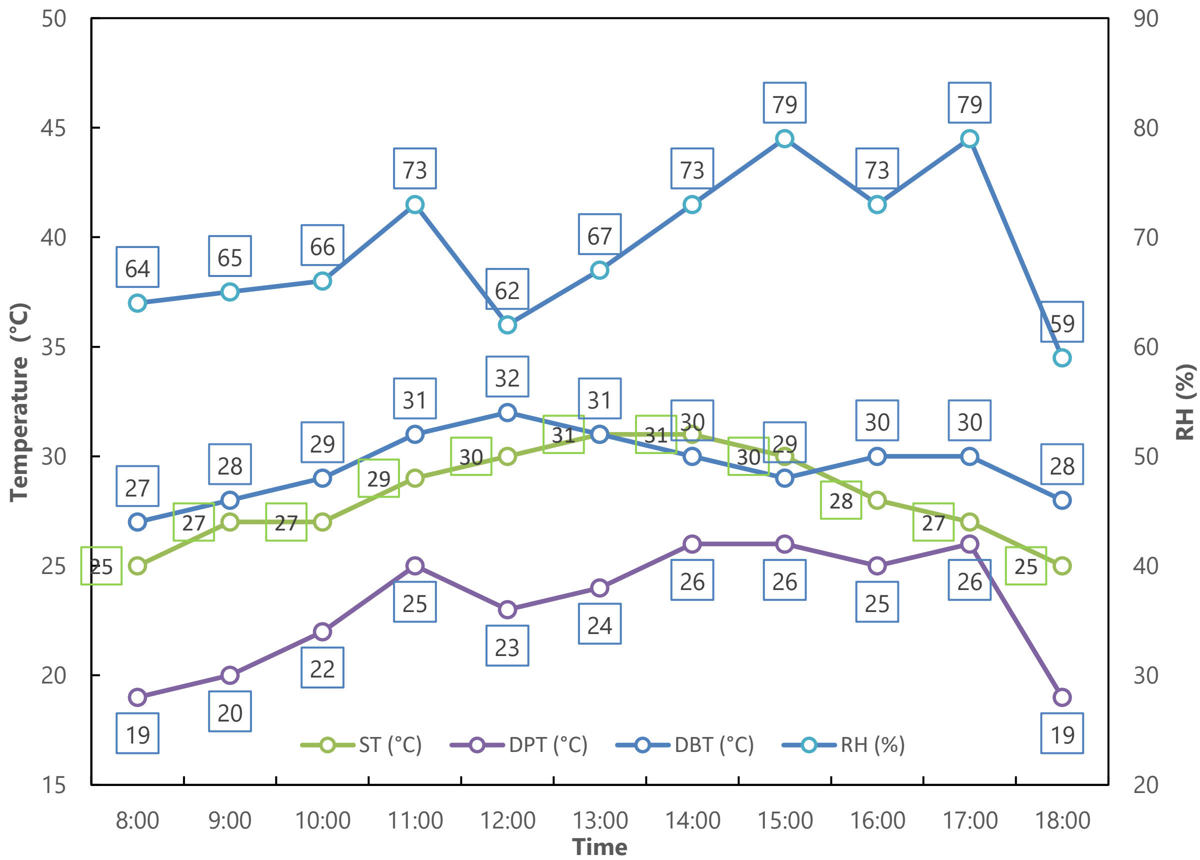

Figure 6. Ambient chart

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P-ISSN : 2339-2029
E-ISSN : 2622-5565

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Website : http://journal.unj.ac.id/unj/index.php/jkem
DOI: https://doi.org/10.21009/JKEM.11.2.6

Environmental condition control is a critical factor in the success of coating application, as parameters such as ST, DPT, DBT, and RH directly affect adhesion mechanisms, film formation, and curing. Based on in-situ measurements presented in the ambient chart (Figure 6), ST ranged from 25°C to 31°C, DPT from 19°C to 26°C, and DBT from 27°C to 32°C. RH ranged from 59% to 79%, with peak values at 14:00 and 16:00. The difference between ST and DPT was generally above the minimum threshold, indicating a low risk of condensation on the steel surface and supporting proper adhesion and curing of the coating.

The trend of environmental conditions throughout the day indicates periods when additional attention may be required to maintain coating quality. Although RH temporarily reached 79%, regular monitoring enabled evaluation of the coating application feasibility at each interval. Therefore, the ambient chart illustrates both environmental variations and provides a technical basis for assessing the suitability of coating application conditions. These data confirm that all environmental parameters remained within the permissible range according to technical standards, minimizing the potential for defects such as blistering, poor adhesion, or premature coating failure.

3.4. Analysis of Primer Coat Application Results

The evaluation of the primer coat application was carried out based on several parameters, including coating thickness, primer DFT, conformity with the specification, and result consistency among the objects. The evaluation method was conducted by measuring the DFT using a DFT gauge, as summarized in the final painting report. The measured values were then compared with the specified technical requirement of 150 µm.

The acceptance criterion at this stage stated that the primer layer was considered acceptable if the DFT value was ≥150 µm and it did not show any extreme deviation that could potentially affect the quality of the coating system. Based on the summarized data, all objects with primer DFT data showed values above the specification. The sole plate of the sag mill had a primer DFT of 186 µm, the cover motor ball mill had 547 µm, the base frame motor bubble crusher had 632 µm, and the OHC girder had 668 µm. This indicates that, quantitatively, all primer applications met and exceeded the specified minimum requirement. The primer DFT evaluation is shown in Table 3.

Table 3. Primer DFT evaluation

Object	Primer specification (µm)	Actual primer DFT (µm)	Difference from specification (µm)	Evaluation
Sole plate sag mill	150	186	+36	Accepted
Cover motor ball mill	150	547	+397	Accepted
Base frame motor bubble crusher	150	632	+482	Accepted
OHC girder	150	668	+518	Accepted

Table 3 shows that the primer DFT achieved on the sole plate of the sag mill was relatively close to the specification. Therefore, it can be considered more proportional to the initial protection requirement, especially considering its initial condition, which had experienced significant degradation. In contrast, the other three objects showed primer DFT values far above the specified requirement. Technically, higher thickness may improve the initial resistance of the coating against the penetration of corrosive media. However, from a descriptive and analytical perspective, this condition also indicates variation in field application control. Excessive coating thickness does not always represent optimal process quality. It may indicate a lack of uniformity in the application technique or insufficient control of the coating process.

In terms of acceptance criteria validation, all objects were declared acceptable because their primer DFT values were above the minimum specified limit. However, from the perspective of process quality, the large variation in coating thickness among the objects shows that application consistency was not fully controlled. Thus, the primer coat application can be considered effective in improving protective performance. However, better control of the application process is still required to achieve a more uniform thickness distribution and closer

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conformity with the design specification. This is important because excessive coating thickness may affect long-term coating performance, including the risk of cracking or imbalance within the coating system [59]-[61].

3.5. Analysis of Top Coat Application Results

The evaluation of the top coat application and the total coating system thickness was analysed based on several parameters, namely final (total DFT), thickness increase compared to the existing condition, and conformity with the technical specification [62], [63]. The evaluation method was carried out by comparing the final DFT data in the final painting report with the top coat specification of 75 µm and the minimum total coating system thickness of 225 µm, which consisted of 150 µm primer and 75 µm top coat.

The acceptance criterion at this stage stated that the coating was considered acceptable if the total DFT was ≥225 µm and showed a significant increase in thickness compared to the initial condition. This increase indicated the formation of a new protective coating system. Based on the data, all objects showed final DFT values above the specification. The sole plate of the sag mill had a final DFT of 295 µm, the cover motor ball mill had 730 µm, the base frame motor bubble crusher had 807 µm, and the OHC girder had 765 µm. The thickness increases compared to the existing DFT were 263 µm, 250 µm, 347 µm, and 289 µm, respectively.

Table 4. Top coat DFT evaluation

Object	Top coat specification (µm)	Actual final DFT (µm)	Increase from existing DFT (µm)	Evaluation
Sole plate sag mill	75	295	263	Accepted
Cover motor ball mill	75	730	250	Accepted
Base frame motor bubble crusher	75	807	347	Accepted
OHC girder	75	765	289	Accepted

Table 4 shows that all inspected objects exceeded the minimum coating system specification, indicating that the recoating process successfully established a protective barrier layer on the steel surfaces. The base frame motor bubble crusher exhibited the highest increase in coating thickness (347 µm), resulting in the highest applied DFT among the evaluated objects. The cover motor ball mill and OHC girder also achieved high final DFT values, which are expected to improve resistance against moisture penetration and corrosive agents. Although the sole plate Sag Mill recorded the lowest final DFT, its thickness remained above the minimum specified requirement, indicating adequate protective performance.

All inspected objects satisfied the acceptance criterion of a minimum total DFT of 225 µm. However, substantial differences in DFT were observed between objects, indicating high inter-object variability in coating application. The final DFT values ranged from 295 µm to 807 µm, corresponding to a variation of approximately 512 µm. This variability suggests inconsistencies in coating deposition and process control during field application. Ideally, coating thickness should remain within the target range specified by the coating manufacturer or project specification to ensure consistent performance and efficient material utilization.

From an engineering perspective, sufficient coating thickness improves barrier protection by reducing the diffusion of moisture, oxygen, and aggressive ions toward the steel substrate. Nevertheless, excessively high DFT values may create overbuilding conditions that increase the risk of solvent entrapment, incomplete curing, internal coating stress, reduced flexibility, cracking, blistering, and premature coating degradation during long-term service. Hence, coating quality should be assessed not only by compliance with minimum thickness requirements but also by the uniformity and consistency of coating application [64], [65].

The observed DFT variability may also influence long-term coating durability. Areas with lower thickness are generally more susceptible to localized corrosion initiation due to reduced barrier protection, whereas excessively thick areas may experience differential curing and stress concentration. These conditions can adversely affect coating adhesion and service life, particularly in industrial environments exposed to cyclic loading, vibration, humidity, and corrosive contaminants [63], [66], [67].

P-ISSN : 2339-2029
E-ISSN : 2622-5565
Volume 11 Number 2 – July 2026 Page 152-169
Website : http://journal.unj.ac.id/unj/index.php/jkem DOI: https://doi.org/10.21009/JKEM.11.2.6

Visual inspection results confirmed that the coating system successfully restored degraded surfaces and produced a continuous protective layer on all inspected components. The acceptable visual condition, combined with DFT values above the specified minimum limit, demonstrates that the coating system fulfilled its primary protective function. Nevertheless, the significant variability in coating thickness indicates opportunities for improving application control, spray technique consistency, and QA/QC procedures. Such improvements would help minimize overbuild conditions, enhance coating uniformity, improve material efficiency, and increase long-term coating reliability.

4. Conclusion

The coating process performed during TPS shutdown maintenance successfully restored the protective function of the inspected industrial components and satisfied all specified technical acceptance criteria. Evaluation of the initial condition revealed varying levels of coating degradation, with existing DFT values ranging from 32 to 480 µm, indicating the need for different surface preparation treatments for each component. The application of the ST 3/SSPC-SP 3 surface preparation method produced surfaces suitable for recoating, as confirmed by the successful application of both primer and top coat layers. All inspected objects achieved primer DFT values above 150 µm and final DFT values exceeding the minimum coating system requirement of 225 µm, with coating thickness increases ranging from 263 to 347 µm.

These results demonstrate that the coating system effectively established a new protective barrier against corrosion. However, the considerable variation in coating thickness among the inspected objects highlights the need for improved control of application parameters, environmental conditions, and QA/QC procedures. Therefore, the effectiveness of a coating system should not be assessed solely by compliance with minimum thickness requirements but also by the consistency of coating application to improve material efficiency, coating reliability, and long-term protective performance in industrial maintenance applications.

5. Acknowledgments

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E-ISSN : 2622-5565

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P-ISSN : 2339-2029
E-ISSN : 2622-5565

Jurnal Konversi Energi dan Manufaktur
Volume 11 Number 2 – July 2026 Page 152-169
Website : http://journal.unj.ac.id/unj/index.php/jkem
DOI: https://doi.org/10.21009/JKEM.11.2.6

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