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Article

Effect of Curing Temperature on Powder Coating Adhesion of ST-37 Steel for Agro-Industrial Machinery Applications

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Abstract: Curing is a critical stage in powder coating because curing conditions influence coating adhesion of ST-37 steel used in agro-industrial machinery and food-processing equipment. Inadequate curing may reduce coating performance and increase the risk of premature coating failure during service. This study investigated the effect of curing temperature on powder coating adhesion by applying three curing temperatures (120°C, 140°C, and 200°C) for 15 minutes. Before coating, ST-37 steel specimens were sandblasted at 4.5 bar to produce a surface roughness profile. Adhesion was evaluated using the cross-cut test (ASTM D3359) and the pull-off test (ASTM D4541). Adhesion increased across the investigated temperatures. Specimens cured at 120°C exhibited the poorest adhesion, classified as 2B–3B with delamination up to 18%, whereas 200°C was the best-performing tested condition, classified as 4B–5B with only 0–2% delamination and pull-off strength of 10.68 ± 0.48 MPa (n=3). The improved adhesion at 200°C is consistent with, but does not directly demonstrate, greater curing and stronger coating–substrate interactions. These findings provide guidance for selecting curing conditions to improve coating adhesion in agricultural and agro-industrial equipment, while corrosion resistance, service life, maintenance, and sustainability require separate evaluation.

Keywords: adhesion, cross-cut test, curing, powder coating, pull-off test, ST-37 steel

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1. Introduction

Powder coating technology has become increasingly important in modern manufacturing due to its environmental friendliness, high efficiency, and excellent mechanical properties compared with conventional liquid coatings. Its near-zero emission of volatile organic compounds (VOC) and high material utilization make it suitable for fabricating agricultural machinery, food-processing equipment, and agro-industrial facilities, where durable and corrosion-resistant surfaces are essential for maintaining operational reliability and reducing maintenance requirements [1]. Indonesia, ST-37 low-carbon steel is widely used in agricultural machinery frames, post-harvest handling equipment, and supporting structures because of its affordability, good weldability, and availability. However, its relatively low corrosion resistance necessitates protective coatings to improve durability and extend service life under humid and corrosive agricultural environments [2]. The curing process is one of the most critical parameters affecting powder coating performance. During curing, thermosetting powder coatings undergo chemical cross-linking reactions that form a stable three-dimensional polymer network. This network strongly influences adhesion strength, hardness, corrosion resistance, and long-term durability [3][4]. Improper curing conditions, such as insufficient temperature or inadequate curing time, may result in incomplete cross-

linking, leading to poor adhesion, premature coating failure, and increased maintenance costs. Conversely, excessive curing may cause thermal degradation and induce internal stresses within the coating layer [5]. For agricultural and food-processing equipment, coating failure may accelerate corrosion, shorten equipment service life, and reduce operational efficiency.

Surface preparation also plays a crucial role in determining coating adhesion. Mechanical treatments such as sandblasting are commonly used to increase surface roughness and improve surface energy, thereby enhancing mechanical interlocking between the coating and the substrate [6]. An incorrect curing temperature can result in poor adhesion of the paint coating, potentially reducing the material's durability and performance [7]. A well-prepared surface ensures better bonding and reduces the risk of delamination during service. Adhesion performance is typically evaluated using standardized methods such as cross-cut testing (ASTM D3359) and pull-off testing (ASTM D4541), which provide qualitative and quantitative measurements of coating-substrate bonding strength [1]. Although previous studies have demonstrated that curing temperature significantly affects coating adhesion and durability, investigations focusing on ST-37 steel for agricultural and agro-industrial applications remain limited, particularly under controlled curing conditions relevant to equipment manufacturing [1], [4], [8]. Therefore, this study investigates the effect of curing temperature on the adhesion performance of powder-coated ST-37 steel using cross-cut and pull-off tests. The findings are expected to provide practical guidance for optimizing powder coating parameters in the manufacture of agricultural machinery and agro-industrial equipment, thereby improving component durability, reducing maintenance requirements, and supporting more sustainable agro-industrial systems.

More specifically, the unresolved question addressed here is how the selected epoxy–polyester hybrid coating responds, in adhesion terms, to substantial under-temperature curing relative to the manufacturer's 200°C recommendation when applied to sandblasted ST-37 steel. Previous work, including reference [18], establishes the general importance of curing temperature, but the present study focuses on the combined interpretation of qualitative cross-cut delamination and quantitative pull-off strength under one controlled substrate-preparation and curing-time protocol. The study therefore tests the hypothesis that increasing curing temperature from 120°C to 200°C improves measured adhesion. Cross-cut testing was used to characterize coating detachment and classification over a cut grid, whereas pull-off testing provided tensile adhesion strength; the two methods were used as complementary indicators rather than as direct measures of corrosion resistance or long-term durability.

2. Materials and Methods

2.1 Research Design

The substrate material used in this study was ST-37 low-carbon steel plate, which is widely utilized in the fabrication of agricultural machinery, food-processing equipment, and agro-industrial supporting structures because of its cost-effectiveness, good weldability, and favorable mechanical properties. Protective powder coatings are commonly applied to these components to improve corrosion resistance, extend service life, and reduce maintenance under agricultural operating conditions. Specimens measured 60 mm × 40 mm. Coating adhesion was evaluated using the cross-cut test and the pull-off test in accordance with ASTM D3359 and ASTM D4541 standards [9].

The three temperature levels were selected to represent two deliberately under-temperature conditions (120°C and 140°C) and the manufacturer's specified standard curing temperature (200°C; Table 2), allowing the adhesion response to incomplete versus recommended thermal exposure to be compared. The available experimental record identifies three specimens per temperature condition; however, random allocation, plate-of-origin allocation, and separate coating-batch information were not documented and are

therefore treated as limitations of the experimental design. Results are reported as individual replicate values where available and as mean ± standard deviation. One-way ANOVA followed by Tukey's HSD test ($\alpha = 0.05$) was used for exploratory comparison among the three curing-temperature groups; because n = 3 per group, statistical inferences are interpreted cautiously.

The independent variable was curing temperature, while the curing time was maintained at 15 minutes for all specimens. The response parameter was coating adhesion, evaluated qualitatively using the cross-cut test and quantitatively using the pull-off test. Each experimental condition consisted of three independent specimens (n = 3) to ensure the repeatability and reliability of the results. The findings are intended to provide guidance for optimizing powder coating processes applicable to the manufacture of agricultural machinery and agro-industrial equipment. The chemical composition and mechanical properties of the material are presented in Table 1.

Table 1. Chemical composition and mechanical properties of ST-37 steel [10]

Element/Property	**Value**
Carbon (C)	0.50%
Silicon (Si)	0.30%
Manganese (Mn)	0.80%
Minimum Tensile Strength	370 MPa
Minimum Yield Strength	235 MPa
Density	7.85 g/cm^3

2.2 Specimen Preparation

Prior to coating, all ST-37 steel specimens underwent surface preparation using a dry sandblasting process to remove contaminants and improve surface roughness. This surface treatment represents a common industrial practice for preparing steel components used in agricultural machinery and agro-industrial equipment before protective coating application. The process parameters were set at a pressure of 4.5 bar, with a blasting angle of 90° and a stand-off distance of approximately 10–15 cm.

After sandblasting, the specimens were cleaned using compressed air to remove residual abrasive particles. The coating process was performed immediately after cleaning to minimize surface oxidation (flash rust) and ensure consistent surface conditions for all specimens, thereby improving the reliability of adhesion evaluation.

2.3 Powder Coating Application

Powder coating was applied using the electrostatic spray coating method, in which electrically charged powder particles were deposited onto the surface of grounded ST-37 steel specimens. This coating technique is widely adopted in the manufacture of agricultural machinery, food-processing equipment, and agro-industrial components because it provides uniform coating thickness, high transfer efficiency, and low environmental impact compared with conventional liquid coatings. The coating material used was **Jotun Facade 1408 (RAL 6018 SMO, green)**, a thermosetting epoxy–polyester hybrid powder coating commonly employed for industrial applications requiring good mechanical performance and corrosion resistance.

Table 2. Technical specifications of powder coating material [11]

Parameter	**Specification**
Resin Type	Thermosetting (Epoxy–Polyester)
Gloss Level (60°)	90 ± 10 GU
Recommended Thickness	60–80 μm
Standard Curing Temperature	200°C
Standard Curing Time	10 min

The manufacturer's recommended dry-film thickness is 60–80 μm (Table 2). Actual film thickness, electrostatic application voltage, detailed gun settings, number of spray passes, and deposited powder mass were not independently recorded in the available experimental dataset. Accordingly, these uncontrolled or undocumented application variables are acknowledged as potential contributors to between-specimen variability, particularly in the pull-off test, and the adhesion results should be interpreted within this limitation.

The 15 min interval was documented as oven curing time at the selected oven set point. Oven model, temperature-control accuracy, calibration records, actual specimen/coating temperature, and time after the coating itself reached the target temperature were not recorded in the available dataset. Therefore, the reported conditions represent nominal oven set-point exposures rather than verified time-at-metal-temperature histories, which limits mechanistic interpretation of the curing response.

The coating was applied using an electrostatic spray gun, where negatively charged powder particles were deposited onto grounded steel substrates. The spraying distance was maintained at approximately 15 cm to ensure uniform coating thickness and coverage across all specimens. This coating technique is commonly employed in the manufacture of agricultural machinery and agro-industrial equipment because it provides high coating efficiency, uniform film formation, and reliable corrosion protection.

2.4 Curing Process

After the coating process, the specimens were placed in an oven for curing for a fixed period of 15 minutes. The materials were cured in the oven at temperatures of 120°C, 140°C and 200°C [12]. The curing process promotes cross-linking of the thermosetting epoxy–polyester powder coating, producing a durable polymer network that enhances coating adhesion and corrosion resistance. Optimizing curing conditions is particularly important for coated steel components used in agricultural machinery and food-processing equipment, where durable protective coatings contribute to longer service life and reduced maintenance requirements.

After curing, coating adhesion was evaluated using two standardized methods. The cross-cut test (ASTM D3359) was performed by making intersecting vertical and horizontal cuts through the coating to assess the degree of coating detachment from the substrate. The pull-off test (ASTM D4541) measured the tensile adhesion strength between the coating and the ST-37 steel substrate using a bonded dolly, providing a quantitative evaluation of coating adhesion [13].

For the cross-cut assessment, classification followed ASTM D3359 based on the observed coating removal from the cut grid. For the pull-off assessment, a 20 mm dolly and epoxy adhesive were used and the observed failure mode was recorded. The available experimental record does not specify the cutter geometry and spacing, tape product and application/removal procedure, epoxy curing conditions, dolly surface-preparation details, or pull-off loading rate. These procedural details should be controlled and reported in future replication because they can affect absolute adhesion values and failure-mode interpretation.

Table 3. Experimental curing conditions

Specimen Group	Temperature (°C)	Time (min)	Number of Samples	Condition
A	120	15	3	Under-curing
B	140	15	3	Intermediate curing
C	200	15	3	Optimal curing

An Arrhenius-type transformation was used only as an exploratory empirical description of the temperature dependence of measured adhesion strength; it was not treated as a direct measurement of chemical curing kinetics.

2.5 Adhesion Testing

Coating adhesion was evaluated using two standardized methods: the cross-cut test (ASTM D3359) and the pull-off test (ASTM D4541). These methods are widely used to assess the durability and reliability of protective coatings applied to steel components in industrial, agricultural, and agro-industrial applications. In the cross-cut test, the coated surface was cut into a grid pattern using vertical and horizontal incisions. The degree of coating delamination was visually assessed to determine the adhesion classification according to ASTM D3359, providing a qualitative evaluation of coating adhesion.

The pull-off test was conducted to obtain quantitative adhesion strength values. A 20 mm diameter dolly was bonded to the coated surface using epoxy adhesive. A perpendicular tensile load was then applied until coating failure occurred. The maximum stress recorded at failure represented the adhesion strength between the coating layer and the ST-37 steel substrate. Adhesion strength was calculated by dividing the applied force by the bonded area. The combination of qualitative and quantitative adhesion evaluations provides a comprehensive assessment of coating performance for protective applications in agricultural machinery and agro-industrial equipment.

The adhesion strength (σ) of the coating was determined using the pull-off test method, which is calculated as the ratio between the maximum applied force and the bonded area. This relationship is expressed as $\sigma = F/A$, where Frepresents the applied tensile force (N) and Adenotes the bonded area (m^2). The resulting adhesion strength is typically expressed in megapascals (MPa). This parameter reflects the coating's ability to resist detachment from the substrate under tensile loading, as given by the formula [13].

The linear, Arrhenius-type, thermal-stress, and energy-based calculations were used as secondary exploratory analyses of the adhesion dataset. The Arrhenius-type fit contains only three temperature-level means; consequently, its apparent activation energy and R^2 are descriptive and cannot establish a chemical kinetic mechanism. Likewise, the thermal-stress and energy-based calculations rely on model parameters rather than coating properties measured in this experiment. Their outputs are therefore interpreted as model-dependent estimates, not independently validated material properties. Because the source dataset does not include experimental uncertainty for these model parameters, a formal sensitivity analysis could not be performed; this is a limitation of the present analysis.

$$\sigma = \frac{F}{A} \quad (1)$$

The adhesion strength follows an Arrhenius-type relationship with temperature, indicating that the curing process is thermally activated.

The extent of coating failure was evaluated using the delamination percentage (D), which quantifies the ratio of the damaged or peeled area to the total tested area. This is calculated using the expression $D = (A_d/A_t) \times 100\%$, where $A_d$is the delaminated area and $A_t$is the total cross-cut test area, both expressed in mm². The delamination percentage provides a quantitative measure of coating integrity, where lower values indicate better adhesion performance and stronger interfacial bonding, as given by the formula [13]:

$$D = \frac{A_d}{A_t}\, x\, 100\% \qquad (2)$$

To evaluate the relationship between curing temperature and adhesion strength, a linear regression model was applied, expressed as $\sigma = aT + b$, where Trepresents the curing temperature (°C or K), $a$is the slope (MPa/°C), and $b$is the intercept (MPa). This model allows for the identification of trends and the quantification of how temperature affects adhesion strength. A positive slope indicates that increasing curing temperature improves adhesion performance. The linear formula is [13]:

$$\sigma = aT + b \qquad (3)$$

The temperature dependence of adhesion strength was further analyzed using the Arrhenius equation, where A is the pre-exponential factor, Ea is the activation energy (J/mol), R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature (K). This model describes the thermally activated nature of the curing process, indicating that higher temperatures accelerate polymer cross-linking reactions, resulting in enhanced adhesion strength, as given by the formula [13]:

$$\ln(\sigma) = \ln(A) - \frac{E_a}{RT} \qquad (4)$$

The effect of thermal mismatch between the coating and substrate was evaluated using the thermal stress model. Where E is the elastic modulus of the coating (Pa), α is the coefficient of thermal expansion (K^{-1}), and $\Delta T$is the temperature difference (K). This model explains how internal stresses develop during heating and cooling cycles. These stresses can significantly influence adhesion performance by either enhancing mechanical interlocking or inducing failure if excessive, as given by the formula [13]:

$$\sigma_{thermal} = E\alpha\Delta T \qquad (5)$$

An energy-based approach was also employed to describe the resistance of the coating to crack propagation. Where $G_c$is the critical energy release rate (J/m²), σ is the adhesion strength (MPa), and E is the elastic modulus (Pa). This parameter represents the energy required to initiate and propagate a crack at the interface. Higher values of G_c indicate stronger adhesion and improved resistance to delamination.

$$G_c = \frac{\sigma^2}{E} \qquad (6)$$

3. Results and Discussion

3.1 Surface Pretreatment and Visual Inspection

Prior to coating application, all specimens underwent a surface pretreatment process using sandblasting to remove contaminants such as rust, oil, and dust from the steel surface. The process was conducted using silica sand propelled by compressed air at a pressure of 4.5 bar and a blasting angle of 90° [14]. As shown in Figure.1a, the untreated surface exhibits visible contamination, including rust and adhered particles, which can

negatively affect coating adhesion. After sandblasting, as presented in Figure.1b, the surface appears significantly cleaner and more uniform, indicating effective removal of impurities.

In addition to cleaning, the sandblasting process also enhances surface roughness, which is essential for improving mechanical interlocking between the coating and the substrate [15]. Proper surface preparation is particularly important for ST-37 steel components used in agricultural machinery and agro-industrial equipment, where exposure to moisture, fertilizers, soil particles, and outdoor operating conditions can accelerate coating degradation and corrosion. A clean and roughened substrate promotes stronger coating–substrate bonding, reducing the likelihood of premature coating failure during service.

Visual examination showed that the specimens had generally uniform-looking surfaces without obvious macroscopic defects such as blistering, peeling, or pinholes. This observation is limited to surface appearance and does not by itself demonstrate adhesion strength, curing completeness, corrosion resistance, or long-term durability; those interpretations require quantitative adhesion tests or additional dedicated measurements.

The photographs also suggest a continuous coating appearance across the three nominal curing conditions. Any slight differences in texture may be associated with temperature-dependent film formation, but the present visual inspection cannot determine the degree of polymer cross-linking because no DSC, FTIR, glass-transition, hardness, or other direct cure measurement was performed.

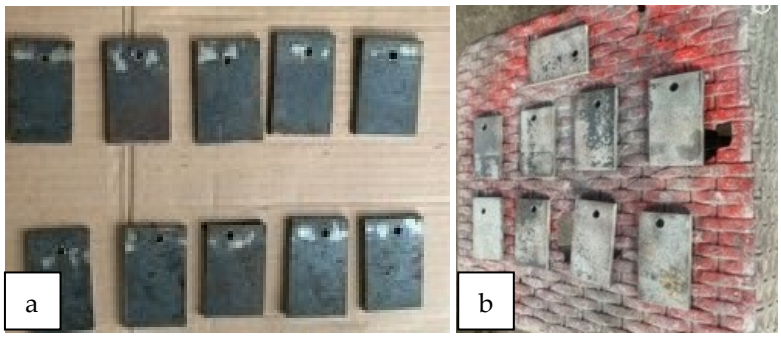


Figure 1. Surface condition of specimens (a) before and (b) after sandblasting.

A visual inspection was conducted to evaluate the surface quality of the coated specimens after pretreatment and powder coating processes under different curing conditions. The curing variations applied were 120°C/15 min, 140°C/15 min, and 200°C/15 min, as presented in Figure 2.

The cross-cut results decreased systematically with increasing curing temperature. The individual delamination values were 10%, 14%, and 18% at 120°C (mean 14 ± 4%); 6%, 9%, and 12% at 140°C (mean 9 ± 3%); and 0%, 1%, and 2% at 200°C (mean 1 ± 1%). The corresponding ASTM D3359 classifications were 2B–3B, 3B, and 4B–5B, respectively. These results directly demonstrate lower coating removal at the higher tested temperatures; explanations involving more complete curing are consistent with thermosetting-coating theory but were not measured directly in this study.

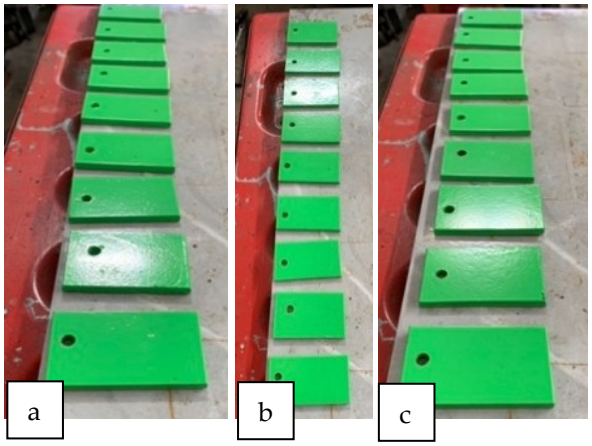


Figure 2. Surface appearance of powder-coated specimens under different curing conditions: (a) 120°C, (b) 140°C, and (c) 200°C.

The visual examination indicates that all specimens exhibit a generally uniform coating layer without significant visible defects such as blistering, peeling, or pinholes. This suggests that the pretreatment process through sandblasting was effective in preparing the substrate surface, allowing proper coating adhesion [16].

Furthermore, the powder coating process successfully produced a continuous and homogeneous film across all curing conditions [17]. The coating particles were able to melt, flow, and form a consistent layer on the substrate surface. Although no major visual defects were observed, slight differences in surface texture may be present, which could be associated with variations in curing temperature and the degree of polymer cross-linking .

Several previous studies have reported findings consistent with the results obtained in this study regarding the influence of curing temperature on powder coating adhesion performance. Reported that insufficient curing temperature resulted in poor coating adhesion and significant delamination during the ASTM D3359 cross-cut test due to incomplete melting and curing of the powder particles. Their study showed that coatings cured at lower temperatures exhibited weak bonding and uneven surface morphology, whereas higher curing temperatures produced more stable and well-adhered coatings [18]. In addition, Andersson demonstrated that increasing curing temperature enhanced cross-linking density within the coating structure, which contributed to improved adhesion and mechanical properties. The study also indicated that proper curing conditions are essential to achieve optimal coating integrity and durability. Furthermore, Yuan et al. explained that higher curing temperatures promote better polymer network formation and improve interfacial bonding between the coating and substrate, resulting in stronger adhesion performance [19]. These findings support the present study, where specimens cured at 200°C exhibited the lowest delamination percentage and the highest adhesion classification.

From an application perspective, improved coating adhesion is particularly beneficial for steel components used in agricultural machinery and agro-industrial equipment that operate under humid, dusty, and corrosive environments. Strong coating–substrate bonding reduces the likelihood of coating failure, thereby minimizing corrosion, extending equipment service life, and lowering maintenance requirements. These improvements can enhance the operational reliability and sustainability of agricultural and agro-industrial systems by reducing equipment downtime and replacement frequency.

Overall, the absence of visible coating defects confirms that the selected coating and curing parameters produced uniform coating quality, ensuring that all specimens were suitable for subsequent adhesion testing and providing practical guidance for powder coating applications in agro-industrial equipment manufacturing.

3.2 Effect of Curing Temperature on Adhesion Performance Cross-Cut Test

The effect of curing temperature on coating adhesion can be clearly observed from the percentage of coating delamination obtained from the cross-cut test results. The data indicate a consistent reduction in the delaminated area as the curing temperature increases. At 120°C, the coating exhibits the highest delamination values, ranging from 10% to 18%, corresponding to classifications between 2B and 3B. This behavior suggests that the curing process at this temperature is insufficient to fully initiate the cross-linking reaction within the thermosetting powder coating. As a result, the coating layer remains mechanically weak and exhibits poor adhesion to the substrate.

When the curing temperature is increased to 140°C, the delamination percentage decreases to a range of 6% to 12%, indicating improved adhesion performance. This improvement can be attributed to partial completion of the polymer cross-linking process, allowing better film formation and enhanced bonding between the coating and the substrate. However, the adhesion strength is still limited, as indicated by the consistent classification of 3B, suggesting that the curing process remains incomplete.

A significant improvement is observed at 200°C, where the delamination percentage drops drastically to 0–2%, corresponding to classifications of 4B to 5B. At this temperature, the coating achieves optimal curing conditions, allowing complete polymer cross-linking and the formation of a dense and stable coating network. This results in strong mechanical interlocking and improved physicochemical bonding between the coating and the substrate (Figure 3).

Figure 4 shows an increasing trend in mean pull-off adhesion strength with curing temperature. The linear fit gives $R^2 = 0.9837$, but this regression is based on only three temperature-level means. Accordingly, the high R^2 should be interpreted as a descriptive fit over the investigated range rather than evidence of a robust predictive relationship or a direct measure of curing kinetics. The increase from 5.66 MPa at 120°C to 10.68 MPa at 200°C is the primary experimental evidence for improved adhesion at the higher tested temperature.

From an engineering perspective, these findings demonstrate that curing temperature is a critical process parameter influencing the reliability of powder-coated steel components. For agricultural machinery and agro-industrial equipment, superior coating adhesion is essential to withstand exposure to moisture, fertilizers, soil particles, cleaning operations, and other corrosive service environments. The excellent adhesion achieved at 200°C is therefore expected to reduce coating delamination, delay corrosion initiation, and improve the long-term durability of coated ST-37 steel components.

The improved adhesion performance obtained under optimal curing conditions also provides practical guidance for powder coating process optimization in agro-industrial manufacturing. By minimizing coating failure and maintenance frequency, appropriate curing conditions can enhance equipment reliability, extend service life, and contribute to more sustainable operation of agricultural and agro-industrial systems.

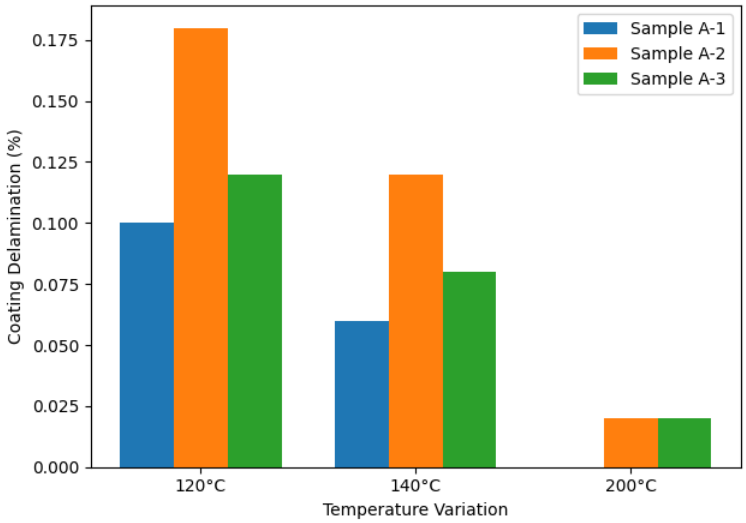


Figure 3. Effect of Curing Temperature on Coating Adhesion Cross-Cut Test.

The relationship between curing temperature and adhesion strength, as illustrated in Figure 4, demonstrates a strong positive correlation, which is well described by a linear regression model with the equation $\sigma = 0.0502T - 0.444$ and a coefficient of determination $R^2 = 0.9837$. This high R^2 value indicates that approximately 98.37% of the variation in adhesion strength can be explained by changes in curing temperature, confirming the robustness of the model. The increasing trend suggests that higher curing temperatures enhance the degree of polymer cross-linking within the coating matrix, resulting in improved load transfer and stronger interfacial bonding between the coating and the substrate. Furthermore, the gradual increase in adhesion strength from 5.66 MPa at 120°C to 10.68 MPa at 200°C indicates that the curing process becomes more effective at higher temperatures, leading to a more homogeneous and mechanically stable coating structure. This behavior is consistent with thermally activated curing mechanisms, where elevated temperatures promote molecular mobility and reaction kinetics, ultimately improving adhesion performance.

The strong correlation between curing temperature and adhesion strength provides an important basis for optimizing powder coating processes used in the manufacture of agricultural machinery and agro-industrial equipment. Improved adhesion strength can enhance resistance to coating failure under harsh operating conditions, including exposure to moisture, fertilizers, soil particles, cleaning agents, and fluctuating environmental conditions. Consequently, optimizing curing temperature can reduce maintenance frequency, extend the service life of coated steel components, and improve equipment reliability. These benefits support more efficient and sustainable agro-industrial operations by reducing material replacement and maintenance-related downtime.

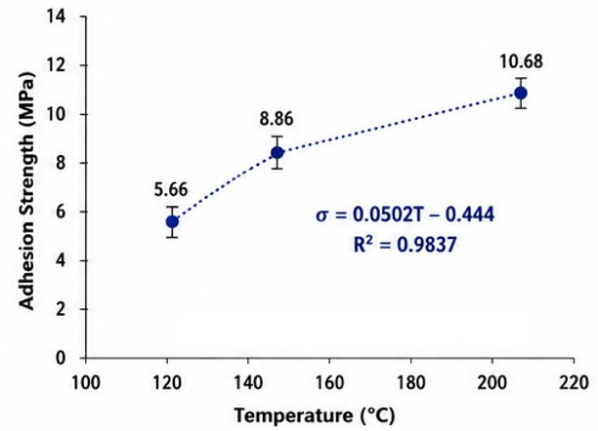


Figure 4. Effect of curing temperature on adhesion strength with a linear regression model.

verall, the cross-cut and pull-off measurements show improved adhesion as curing temperature increased within the tested range. Established powder-coating theory provides a plausible explanation through improved melting, flow, and thermoset network development at higher temperature; however, the present experiment measured adhesion rather than polymer cross-linking directly [20]. Conversely, insufficient curing temperature results in incomplete film formation and weak adhesion.

Among the three tested conditions, 200°C for 15 minutes was the best-performing condition, producing the lowest delamination and the highest adhesion classification. This wording is intentionally limited to the investigated temperatures and does not establish a global optimum outside the tested range.

From an engineering standpoint, stronger coating adhesion is relevant to the integrity of powder-coated ST-37 components used in agricultural and agro-industrial applications. However, corrosion resistance, mechanical damage tolerance, service life, and performance under humid or chemically aggressive environments were not measured in this study and should not be inferred from adhesion alone.

The findings therefore provide guidance for selecting curing conditions when adhesion is the performance criterion. Potential effects on maintenance frequency, lifecycle cost, corrosion protection, and sustainability remain application-level implications that require dedicated corrosion, durability, and lifecycle testing.

These findings confirm that curing temperature is a critical parameter in the powder coating process, directly influencing coating integrity and adhesion quality. The optimal curing condition identified in this study is **200°C for 15 minutes**, which produces the lowest delamination and the highest adhesion classification.

From an engineering standpoint, optimizing curing temperature is essential for improving the durability and corrosion resistance of powder-coated ST-37 steel components used in agricultural machinery, food-processing equipment, and other agro-industrial applications. Enhanced coating adhesion reduces the risk of premature coating failure, thereby protecting steel substrates from corrosion and mechanical damage during operation in humid, dusty, and chemically aggressive environments.

The 200°C condition gave the highest measured pull-off adhesion among the tested groups (10.68 ± 0.48 MPa). This result is consistent with more effective curing at the

manufacturer's recommended temperature, but it does not by itself demonstrate complete cross-linking or identify the molecular mechanism responsible for adhesion.

3.2 Effect of Curing Temperature on Adhesion Strength Pull-Off Test

The pull-off test results demonstrate a clear dependence of adhesion strength on curing temperature, illustrated in figure 5. The average adhesion strength increased significantly from 5.66 MPa at 120°C to 8.86 MPa at 140°C, and reached a maximum of 10.68 MPa at 200°C. At 120°C, the coating exhibits the lowest adhesion strength, ranging from 5.55 to 5.75 MPa. This relatively low value indicates insufficient curing, where the polymer cross-linking reaction is incomplete. As a result, the coating layer lacks structural integrity and exhibits weak bonding with the substrate. This condition is further supported by the relatively high occurrence of adhesive failure, indicating that detachment occurs at the interface between the coating and the substrate.

At 140°C, the adhesion strength improves significantly, with values ranging from 6.93 to 11.23 MPa. This variation suggests that the curing process is partially effective but not yet fully stable. The presence of both high and moderate adhesion values indicates that the cross-linking process begins to develop, although it may not be uniform across all specimens. This condition is reflected in the mixed failure modes observed, including adhesive and cohesive failures (Figure 5).

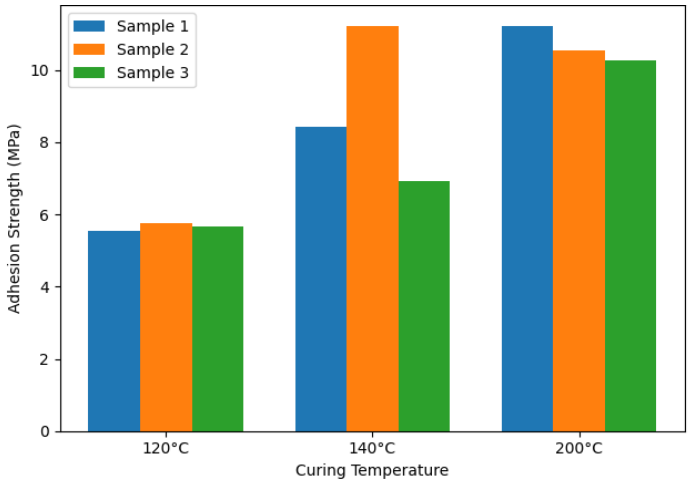


Figure 5. Effect of Curing Temperature on Adhesion Strength Pull-Off Test.

The highest adhesion strength is achieved at 200°C, with values ranging from 10.28 to 11.21 MPa, and an average of 10.68 MPa. At this temperature, the curing process is considered optimal, enabling complete polymer cross-linking and the formation of a dense and stable coating structure. This results in stronger interfacial bonding and improved mechanical interlocking between the coating and the substrate.

Furthermore, the dominance of glue failure at 200°C indicates that the adhesive bond between the coating and substrate exceeds the strength of the epoxy adhesive used to attach the dolly. This is a strong indication that the coating adhesion has reached a high-performance level.

The Arrhenius-type plot in Figure 6 provides an exploratory linearization of ln(adhesion strength) against reciprocal absolute temperature using only the three temperature-level means. The fitted slope corresponds to an apparent activation energy of approximately 27.93 kJ/mol. Because adhesion strength is a macroscopic response influenced by coating thickness, surface condition, failure mode, and curing history, it is not equivalent to a

chemical reaction rate. Therefore, the high R^2 from three points cannot establish Arrhenius curing kinetics; the value is reported only as an empirical descriptor of the temperature dependence observed in this dataset.

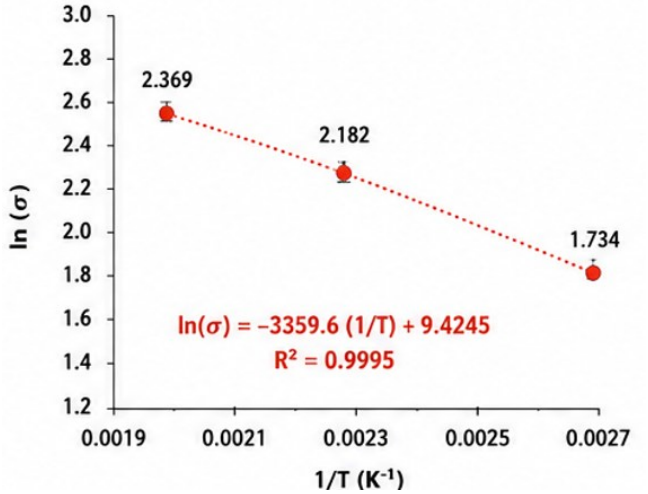


Figure 6. Arrhenius plot of adhesion strength as a function of reciprocal temperature.

Figure 7 illustrates the relationship between curing temperature and the percentage of coating delamination obtained from the cross-cut adhesion test. The results reveal a significant decrease in delamination with increasing curing temperature, following the regression equation $D = -0.108T + 26.68$ with a high coefficient of determination ($R^2 = 0.9904$). This strong negative correlation indicates that curing temperature plays a dominant role in improving coating integrity and adhesion performance. At 120°C, the coating exhibited the highest delamination percentage (14%), suggesting incomplete curing and insufficient polymer cross-linking. As the curing temperature increased to 140°C, the delamination decreased to 9%, indicating partial improvement in coating cohesion and substrate bonding. The lowest delamination value was observed at 200°C (1%), indicating that optimal curing conditions promote the formation of a dense, stable polymer network with stronger interfacial adhesion. The reduction in delamination can also be associated with improved melting, flow, and wetting behavior of powder particles at elevated temperatures, resulting in enhanced mechanical interlocking and cohesive strength within the coating layer. These findings confirm that higher curing temperatures significantly improve coating durability and resistance to interfacial failure.

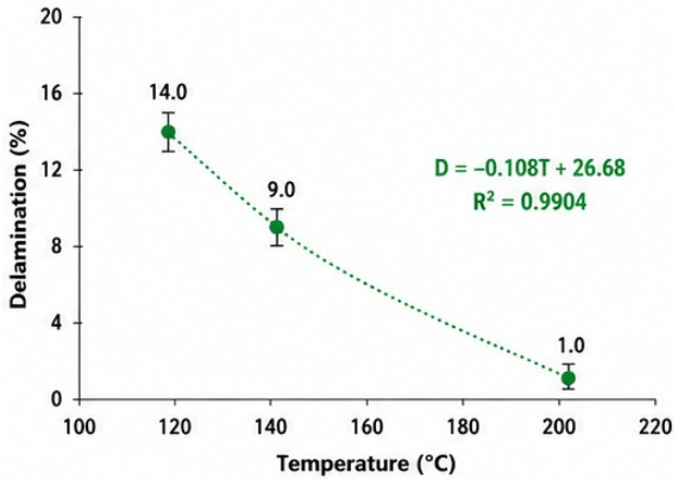


Figure 7. Effect of curing temperature on coating delamination percentage with regression analysis.

Figure 8 presents the relationship between adhesion strength and delamination percentage, showing a strong inverse correlation described by the power-law equation $\sigma = 11.633D^{-0.392}$ with a coefficient of determination $R^2 = 0.9921$. The high R^2 value indicates that the proposed model accurately represents the experimental behavior of the coating system. The graph demonstrates that adhesion strength decreases significantly as the delamination percentage increases, confirming that coating failure is strongly associated with weak interfacial bonding and insufficient curing performance. Specimens with low delamination values (approximately 1%) exhibited the highest adhesion strength (10.68 MPa), indicating the formation of a dense and highly cross-linked polymer structure with superior coating integrity. In contrast, specimens with higher delamination percentages (14%) showed substantially lower adhesion strength (5.66 MPa), suggesting incomplete polymer curing and poor mechanical interlocking between the coating and substrate. The nonlinear trend observed in the graph further indicates that small increases in delamination at low percentages can cause a significant reduction in adhesion performance. This behavior confirms that delamination percentage can be used as a reliable indicator of coating adhesion quality and structural stability.

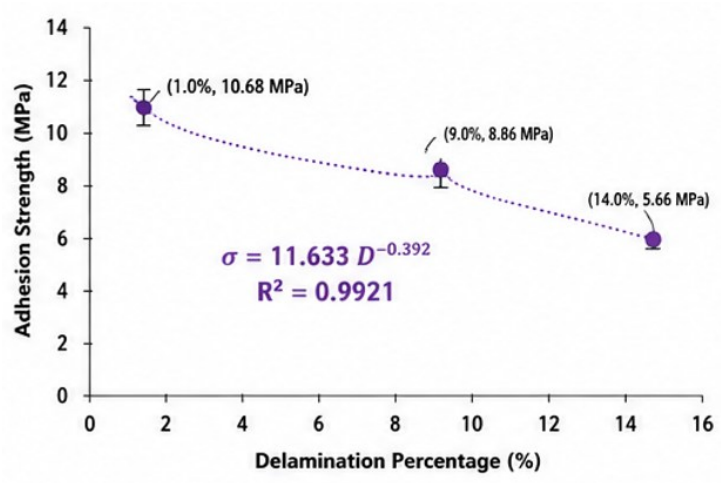


Figure 8. Relationship between delamination percentage and adhesion strength using a power-law regression model.

Figure 9 repeats the Arrhenius-type representation to show how the apparent activation-energy estimate was obtained. With only three temperature levels, the near-linear fit is mathematically sensitive to the small dataset and does not demonstrate the underlying chemical curing mechanism. The analysis should therefore be regarded as exploratory and hypothesis-generating rather than kinetic validation. The linear relationship between $\ln(\sigma)$and $1/T$demonstrates that the adhesion formation process follows thermally activated kinetics, consistent with the Arrhenius equation. The regression model obtained, $\ln(\sigma) = -3359.6(1/T) + 9.4245$, exhibits an exceptionally high coefficient of determination ($R^2 = 0.9995$), indicating excellent agreement between the experimental data and the theoretical model. The negative slope of the Arrhenius plot confirms that increasing curing temperature enhances the adhesion strength by accelerating polymer cross-linking reactions within the powder coating system.

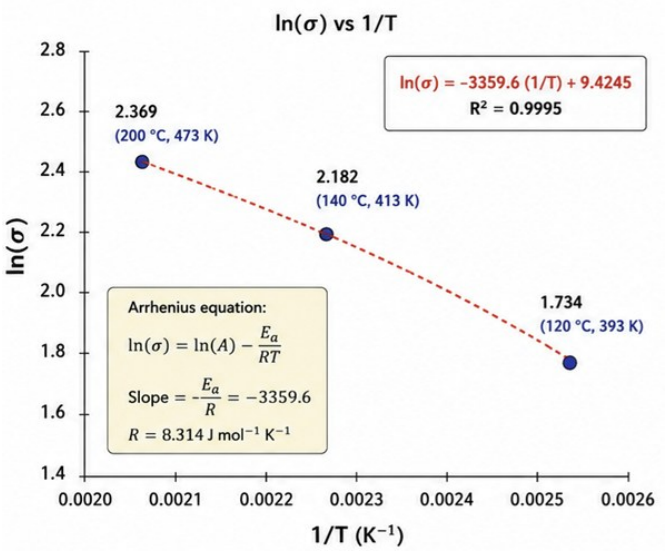


Figure 9. Arrhenius plot and activation energy analysis of adhesion strength during the curing process

Based on the slope of the regression line, the activation energy (E_a) was calculated using the Arrhenius relationship, resulting in a value of approximately 27.93 kJ mol^{-1}. This activation energy represents the minimum thermal energy required to initiate and sustain the curing and adhesion formation processes. The relatively moderate activation energy indicates that the coating system is sensitive to curing temperature variations and can achieve efficient cross-linking under appropriate thermal conditions. At higher curing temperatures, increased molecular mobility and enhanced polymer chain interaction contribute to the formation of a denser and more homogeneous coating network, leading to improved adhesion performance and reduced delamination. These findings are consistent with the pull-off and cross-cut test results, where specimens cured at 200°C exhibited the highest adhesion strength and superior coating integrity.

Furthermore, the strong linearity observed in the Arrhenius plot suggests that the curing process is predominantly governed by temperature-dependent reaction kinetics rather than random physical interactions. This confirms that curing temperature is a critical parameter controlling the interfacial bonding mechanism between the coating and the ST-37 steel substrate.

Several previous studies have also reported a strong dependence of pull-off adhesion strength on curing temperature in thermosetting powder coating systems. Insufficient curing temperature leads to incomplete polymer cross-linking, resulting in weak interfacial bonding and lower adhesion strength measured by pull-off testing. As the curing temperature increases, the polymer network becomes more densely cross-linked, thereby improving both cohesive strength within the coating and adhesive strength at the coating–substrate interface [21]. Curing condition demonstrated that coatings cured at optimal temperatures exhibit significantly higher pull-off adhesion values due to improved wetting, flow, and polymer chain interdiffusion during curing. The higher curing temperatures enhance both mechanical interlocking and chemical bonding, often resulting in a transition of failure modes from adhesive failure to cohesive or glue failure. These findings are consistent with the present study, where the highest adhesion strength and dominant glue failure were observed at 200°C, indicating that the coating–substrate bond strength exceeded the adhesive strength used in the pull-off test.

On the other hand, Figure 10 illustrates the relationship between curing temperature and the critical energy release rate (G_c) based on the energy approach model $G_c = \sigma^2/E$. The results show a substantial increase in G_c with increasing curing temperature, indicating improved resistance of the coating system to crack propagation and delamination. At 120°C, the calculated energy release rate was 11.69 kJ m^{-2}, which increased to 20.86 kJ m^{-2} at 140°C and reached a maximum value of 34.40 kJ m^{-2} at 200°C. This significant increase demonstrates that higher curing temperatures produce a more mechanically stable and structurally integrated coating layer.

The increase in G_c can be attributed to enhanced polymer cross-linking and improved interfacial bonding between the powder coating and the ST-37 steel substrate. As the curing temperature rises, the coating undergoes more complete melting, flow, and molecular rearrangement, leading to the formation of a denser three-dimensional polymer network. This improved microstructural integrity increases the amount of energy required to initiate and propagate cracks within the coating system.

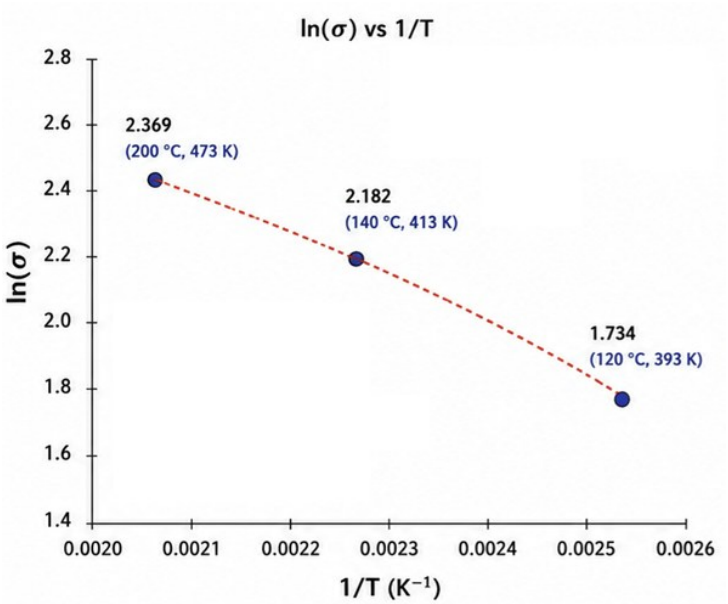


Figure 10. Effect of curing temperature on the critical energy release rate (G_c) of the coating system.

Furthermore, the energy-based analysis indicates that specimens cured at higher temperatures possess greater resistance to coating failure mechanisms such as delamination and interfacial fracture. The highest G_c value observed at 200°C confirms that the optimal curing condition provides superior coating durability and adhesion performance. These findings are consistent with the pull-off and cross-cut test results, where higher curing temperatures resulted in increased adhesion strength and lower delamination percentages.

The energy approach therefore provides an additional theoretical perspective for understanding coating integrity beyond conventional adhesion measurements. The strong correlation between curing temperature and energy release rate confirms that thermal curing significantly influences the fracture resistance and long-term reliability of the coating system.

Figure 11 presents the relationship between curing temperature and the calculated thermal stress ($\sigma_{thermal}$) based on the thermal stress model $\sigma_{thermal} = E\alpha\Delta T$. The results indicate that thermal stress increases significantly with increasing curing temperature,

rising from 24.75 MPa at 120°C to 37.13 MPa at 140°C and reaching 65.98 MPa at 200°C. This trend demonstrates that higher curing temperatures generate greater thermal expansion mismatch between the powder coating layer and the ST-37 steel substrate, leading to the development of internal stresses within the coating system.

The increase in thermal stress is strongly associated with enhanced polymer cross-linking and improved mechanical interlocking at elevated temperatures. During the curing process, thermal energy promotes molecular mobility and facilitates the formation of a denser three-dimensional polymer network. As the coating cools after curing, differences in thermal expansion coefficients between the coating and substrate induce residual stresses that contribute to stronger interfacial bonding. Consequently, specimens cured at higher temperatures exhibit superior adhesion performance and lower delamination percentages.

However, the thermal stress model also suggests that excessively high thermal stress may potentially induce coating defects such as cracking or residual stress accumulation if the stress exceeds the strain tolerance of the coating material. In the present study, the curing condition at 200°C appears to provide an optimal balance between thermal activation and structural stability, resulting in the highest adhesion strength and best coating integrity.

Overall, the experimental evidence is limited to adhesion performance: higher tested curing temperatures were associated with higher pull-off strength and lower cross-cut delamination, with 200°C/15 min performing best among the three conditions. Explanations involving melting, flow, and cross-linking are mechanistic interpretations consistent with established powder-coating behavior, not direct measurements from this experiment. The results are relevant to process selection for ST-37 components, while corrosion resistance, service life, maintenance reduction, and sustainability require separate validation.

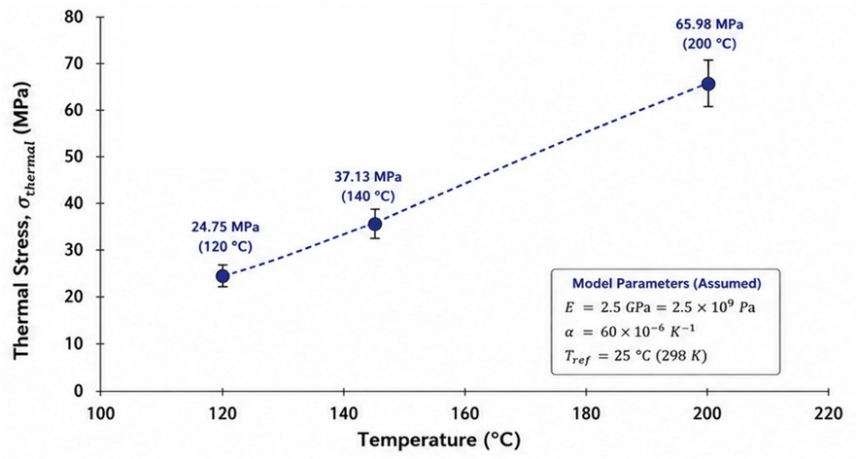


Figure 11. Effect of curing temperature on thermal stress development in the coating system.

The principal practical conclusion is therefore restricted to adhesion: 200°C/15 min was the best-performing tested condition for the powder-coated ST-37 specimens. The results support further process optimization, but claims regarding corrosion protection, equipment service life, maintenance efficiency, and sustainability should be evaluated through dedicated corrosion, durability, and lifecycle studies before being generalized to agro-industrial service conditions.

4. Conclusions

Based on the experimental results and additional theoretical analyses, it is evident that curing temperature significantly influences the adhesion quality of powder coating on ST-37 steel. The cross-cut and pull-off tests consistently show that higher curing temperatures markedly enhance coating adhesion, decrease delamination, and improve overall coating integrity. The coating cured at 120°C displayed poor adhesion, characterized by high delamination and low adhesion strength, suggesting incomplete curing and limited polymer cross-linking. Conversely, samples cured at 140°C and particularly at 200°C demonstrated notable improvements in adhesion, attributed to more effective thermal activation during curing. These findings provide practical guidance for optimizing powder coating processes used in the manufacture of agricultural machinery, food-processing equipment, and other agro-industrial components fabricated from ST-37 steel. The regression analysis further confirmed a strong positive correlation between curing temperature and adhesion strength, with a high coefficient of determination ($R^2 = 0.9837$), indicating that curing temperature is the dominant factor affecting coating performance. The Arrhenius analysis revealed that the adhesion formation process follows thermally activated kinetics, as evidenced by the excellent linear relationship between ln (σ)and $1/T$($R^2 = 0.9995$). The calculated activation energy of 27.93 kJ mol^{-1} suggests that the curing process is highly sensitive to temperature changes, where higher temperatures accelerate polymer cross-linking reactions and improve molecular interaction within the coating matrix.

Moreover, the thermal stress analysis showed that raising the curing temperature results in greater thermal stresses caused by the mismatch in thermal expansion between the coating and the substrate. When these stresses are effectively distributed—especially at 200°C—they enhance mechanical interlocking and the interfacial bond, leading to the coating's optimal adhesion performance. In addition, the energy-based adhesion model showed that the critical energy release rate (G_c) increased significantly with curing temperature, indicating greater resistance to crack propagation and delamination. The highest $G_c$value obtained at 200°C confirms that the coating system requires more energy to initiate failure, reflecting superior structural stability and fracture resistance. The inverse relationship between adhesion strength and delamination percentage further reinforces these results, showing that coatings with less delamination have notably higher adhesion strength and better interfacial integrity.

In summary, combining experimental data with linear regression, Arrhenius kinetics, thermal stress analysis, and energy-based modeling offers a thorough understanding of the adhesion mechanism of powder coatings on ST-37 steel. The optimal curing condition was determined to be 200°C for 15 minutes, achieving excellent adhesion, improved coating integrity, and greater durability. These insights are practical for refining powder coating processes in manufacturing agricultural machinery, food-processing equipment, and other agro-industrial parts. Proper curing conditions can enhance corrosion resistance, lower maintenance needs, extend equipment lifespan, increase operational reliability, and promote more sustainable agricultural and agro-industrial systems.

5. Patents

No patents have been granted in connection with the research reported in this manuscript.

Supplementary Materials: None

Author Contributions: For research articles with multiple authors, a short paragraph specifying each author's individual contributions must be provided. The following statements should be used: "Conceptualization, Riyan Ahla Atilla and Andik Irawan; methodology, Riyan Ahla Atilla and Andik Irawan; software, Andik Irawan; validation, Andik Irawan and Endar Hidayat; formal

analysis, Andik Irawan; investigation, Riyan Ahla Atilla; resources, Riyan Ahla Atilla; data curation, Riyan Ahla Atilla and Andik Irawan; writing—original draft preparation, Riyan Ahla Atilla and Andik Irawan.; writing—review and editing, Andik Irawan and Endar Hidayat.; visualization, Andik Irawan.; supervision, Andik Irawan.; project administration, Riyan Ahla Atilla and Endar Hidayat.; funding acquisition, none. All authors have read and agreed to the published version of the manuscript."

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