

Optimizing Surface Preparation Parameters to Enhance Adhesion of Protective Paints on Mild Steel Plates

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Abstract – The durability and corrosion resistance of protective coatings in agricultural machinery are significantly influenced by the adhesion quality of the applied paint. Poor adhesion leads to premature paint failure, increasing maintenance costs and reducing equipment lifespan. This study aimed to optimize surface preparation parameters – specifically surface roughness, application method, and inclusion of primer paint – to enhance paint adhesion on mild steel plates using two commonly used paint types – acrylic and enamel paints. Mild steel plates were prepared using silicon carbide sandpapers of varying grit sizes (60, 180, 360, 600) to modify surface roughness. Acrylic and enamel paints were applied using both brushing and spraying methods, either with no primer, with primer, or with sanded primer under the topcoat. A total of three paint systems were investigated – topcoat only (TO), primer plus topcoat (PT), and sanded primer plus topcoat (SPT). Paint adhesion was evaluated using Tape Test method (ASTM 3359) and quantified using ImageJ image processing software. Data were statistically analyzed using ANOVA and numerical optimization. Results showed that surface roughness significantly affects adhesion, with coarser sandpaper (grit size 60) yielding the lowest percentage of paint removed. Spraying resulted in better adhesion compared to brushing, and the inclusion of primer consistently improved adhesion in both paint types. Numerical optimization revealed that the optimal combination of grit size 60, spraying application, and PT system produced the best adhesion performance, achieving 5B classification, indicating no paint removal. This study demonstrates that careful selection of surface preparation parameters can substantially improve paint adhesion, thereby enhancing the protective performance of paints in agricultural applications. The methodology and findings provide practical insights for improving paint reliability in harsh environments.

Keywords: paint adhesion, surface preparation, surface roughness, application method, primer paint

I. INTRODUCTION

Agricultural machineries facilitate efficient cultivation, harvesting, and processing of crops on a large scale. These machines are frequently exposed to moisture and soil, making it critical to its durability and reliability is the protective paint applied to its surface to serve as a barrier against corrosion, abrasion, and degradation. Ensuring durable protective paint not only extends the service life of agricultural machinery, but also minimizes maintenance costs and potential downtimes, leading to maximized operational efficiency. One critical property of protective paints is adhesion [1].

Paint needs to fully adhere to the surface to act as a barrier. Sites of poor adhesion become sites of penetration for corrosive elements such as moisture and oxygen, which later can become initial sites of corrosion [1]. To achieve quality paint adhesion, crucial factors such as surface preparation must be considered [2]. Several studies suggests that aside from chemical

bonding, paint adhesion is greatly affected by the physical/mechanical interlocking of surfaces [3–6] (Figure 1). This explains how increasing surface roughness improves adhesion because as surface roughness increases, the surface area for physical coupling also increases [7].

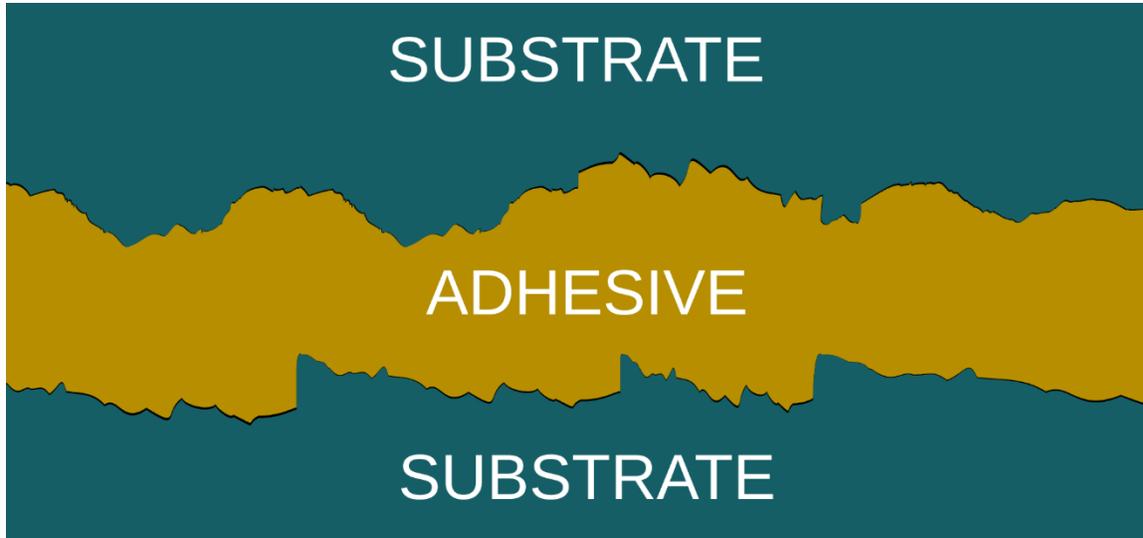


Figure 1. Physical/mechanical interlocking adhesion mechanism on polymer surface [3]

However, increasing surface roughness makes it difficult for paint to penetrate some areas which can lead to gaps or voids which can instead become sites of corrosion (Figure 2)[1]. Therefore, selecting an appropriate application method becomes equally critical. Studies revealed that different application methods such as dipping, brushing, and spraying can significantly affect the quality of paint [8].

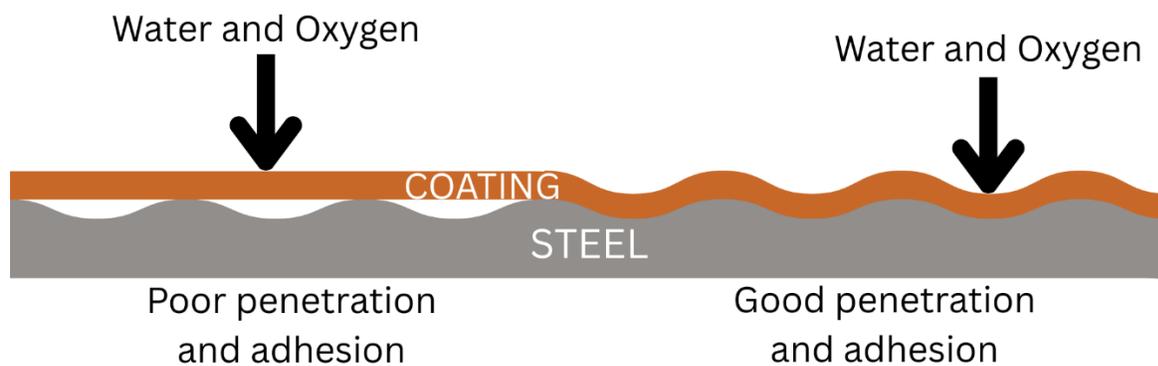


Figure 2. Poor adhesion due to poor penetration [1]

Another crucial factor in paint adhesion is the application of primer paints before the topcoat paints. Primer paints do not just improve adhesion through physical coupling, but also through chemical bonding due to the compatibility of primer and topcoat paints [9].

This study aimed to systematically investigate the impact of different surface preparation parameters such as surface roughness, application method, and primer paint on paint adhesion on mild steel plates. Paint adhesion was quantified using Tape Test method and ImageJ image processing software and was then analyzed using ANOVA.

II. METHODOLOGY

2.1 Substrate Preparation

Mild steel plates (Figure 3) of 3x3-inches in dimension and 3-mm in thickness were used as substrate. Each mild steel plate was sanded using silicon carbide sandpapers with grit sizes of 60, 180, 360, and 600 using aligned strokes to increase roughness and consequently increase adhesion [10]. The substrates were then cleaned and dried.



Figure 3. Mild steel plates used as substrate.

2.2 Paint Application

The two paint types used were acrylic and enamel type, with each corresponding primer and topcoat (Figure 4). Each paint type was applied by brushing and spraying following each manufacturer's instructions and was tested following ASTM D1640-14 [11]. For each paint type, two coats were applied with 3.5 hours interval between coats. Each primer paint was dried and cured for 24 hours, and each topcoat paint was dried and cured for 7 days.

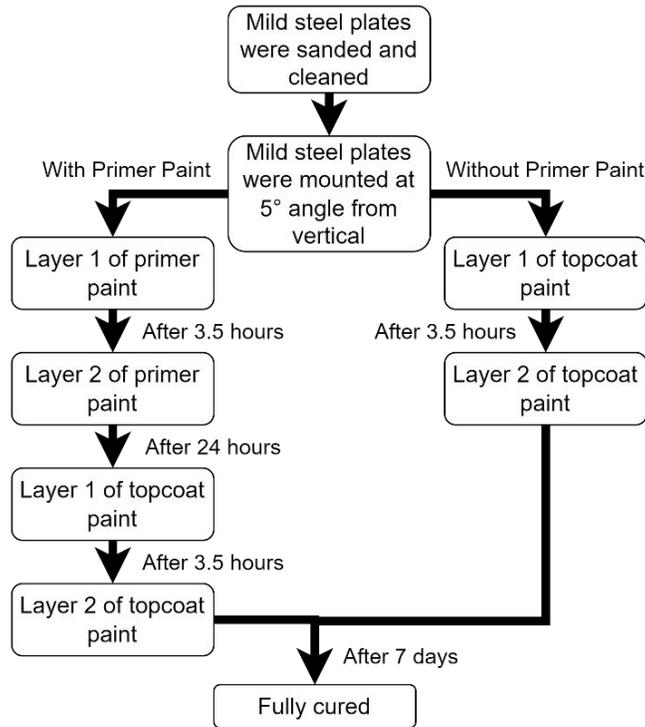


Figure 4. Schematic diagram for sample preparation

Three paint systems were created (Figure 5). For the topcoat only (TO) system, topcoat paints were applied directly on the surface. For the primer + topcoat (PT) system, the corresponding primer paint was applied before applying the topcoat. For the sanded primer + topcoat (SPT) system, the primer paint was sanded using a grit size of 1000 before applying the topcoat paint.

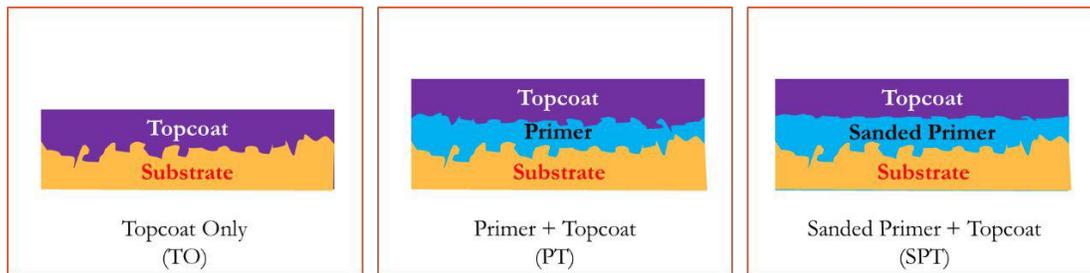


Figure 5. Fabricated paint systems

2.3 Adhesion Testing using Tape Test Method [12]

The paint adhesion of each sample was evaluated using tape test method that was quantified using ImageJ image processor. This method was used to assess relative adhesion using a pressure-sensitive tape. A sharp utility cutter knife was used to create eleven (11) 20mm-long parallel cuts, 1mm apart, with additional cuts made perpendicular to the center as shown in Figure 6.

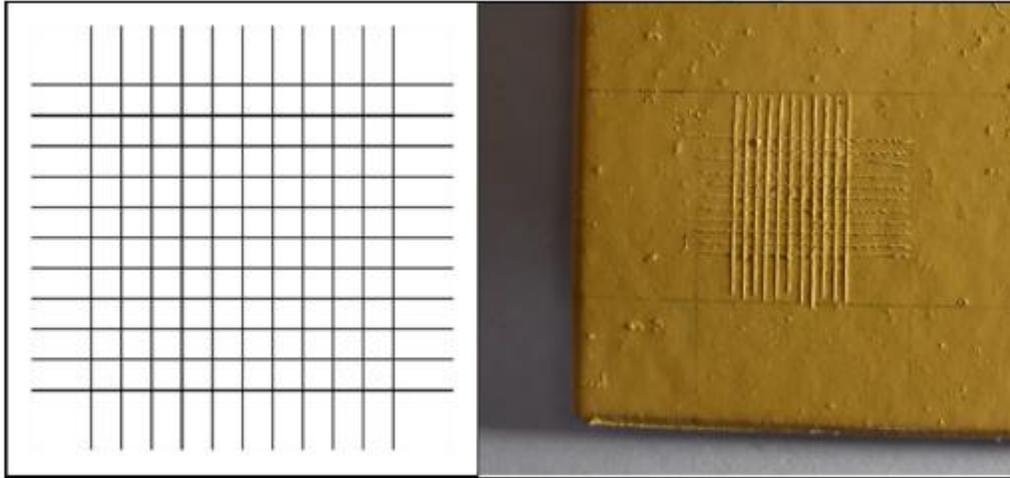


Figure 6. Grid of cuts for tape test method.

A 3in-long pressure-sensitive tape was then placed in the grid and rapidly removed. The test was conducted at three different locations per sample – corner, center, and side (Figure 7). Areas 0.25in from the edges were not tested to eliminate any edge effects. The effects of sandpaper grit size, application method, and inclusion of primer paint were evaluated.



Figure 7. Test locations for tape test method

2.4 Data Analysis

The adhesion test results, expressed as the percentage of paint area removed from each sample, were analyzed using Analysis of Variance (ANOVA) to assess the effects and interactions of grit size, application method, and inclusion of primer paint. A full factorial design was used. Data transformation was performed to satisfy ANOVA assumptions such as normality and homogeneity.

All statistical analyses were conducted using Design-Expert ® software, which also generated the main effect and interaction plots. Numerical optimization was performed to identify the combination of factors that minimized the percentage of area removed. The optimized combination was validated through experimental testing.

III. RESULTS AND DISCUSSION

3.1 Average Thickness

All paint types were successfully applied on the prepared mild steel plates. The average thickness for each paint system and paint type are summarized in Table 1. Both paint types were fabricated with thicknesses within the acceptable tolerance specified in each product sheets.

Table 1. Summary of thickness of each paint system for both paint types

PAINT TYPE	PAINT SYSTEM*	MEAN (μm)	SD (μm)	Coefficient of Variation (%)
Acrylic	TO	147.14	7.62	5.18
	PT	229.71	12.71	5.53
	SPT	181.43	16.17	8.91
Enamel	TO	147.20	8.45	5.74
	PT	230.00	11.66	5.07
	SPT	174.40	13.53	7.76

*TO – topcoat only, PT – primer + topcoat, SPT – sanded primer + topcoat

3.2 Surface Topography

Based on the AFM measurements (Figure 8), both primer paints exhibit moderate to high level of roughness (Ra) which promotes adhesion between the primer and topcoat paints. Conversely, both topcoat paints exhibit low levels of roughness, which is good for withstanding corrosive elements such as moisture. Moreover, all paint types exhibit high levels of height deviations (Rq) and maximum height profile (Rz), which indicates irregular surface topography.

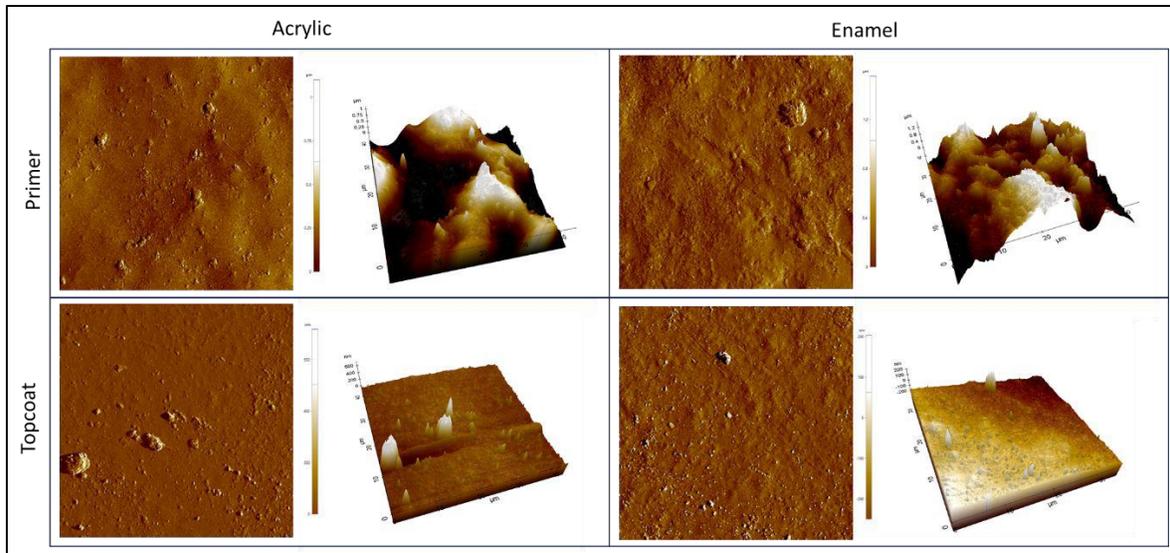


Figure 8. Surface topography of each paint type

3.3 Main Effects of Factors

Using ANOVA, $F(6,17) = 36.45$, $p < 0.0001$, and a square root transformation ($\lambda=0.5$), it was observed that the main effects of grit size, application method, and primer inclusion significantly affected the percentage of area removed for acrylic paint. On the other hand for enamel paint, all three factors also significantly affected the percentage of area removed including the interaction of application method and paint system, $F(8,15) = 42.31$, $p < 0.0001$. Thus, individual effects can be independently interpreted for acrylic paint, and the main effect of sandpaper grit size and the interaction of application method and paint system for enamel paint.

3.4 Effects of Sandpaper Grit Size

On the average, as the sandpaper grit size was increased, the percent area removed using tape test method also increased (Figure 9). The lowest predicted mean of 17.54% (2B rating) and 7.78% (3B rating) was observed using a grit size of 60 for both acrylic and enamel paint, respectively, while the highest predicted mean of 44.48% (1B rating) and 15.25% (2B rating) was observed using a grit size of 600, respectively. This suggests that coarser sandpaper grit size can improve paint adhesion as it is also observed in previous studies. Rincon Troconis and Frankel (2013) was able to show how adhesion strength “monotonically” increased with roughness using Silicon carbide sandpapers on aluminum alloys [10]. While more recently, Maroofi, et al. (2020) was able to improve adhesion ratings from 1B to 5B using atmospheric cold plasma jet on aluminum surface [13]. Moreover, visual inspection and optical microscopy showed no significant difference in the appearance of paint samples (Figure 10).

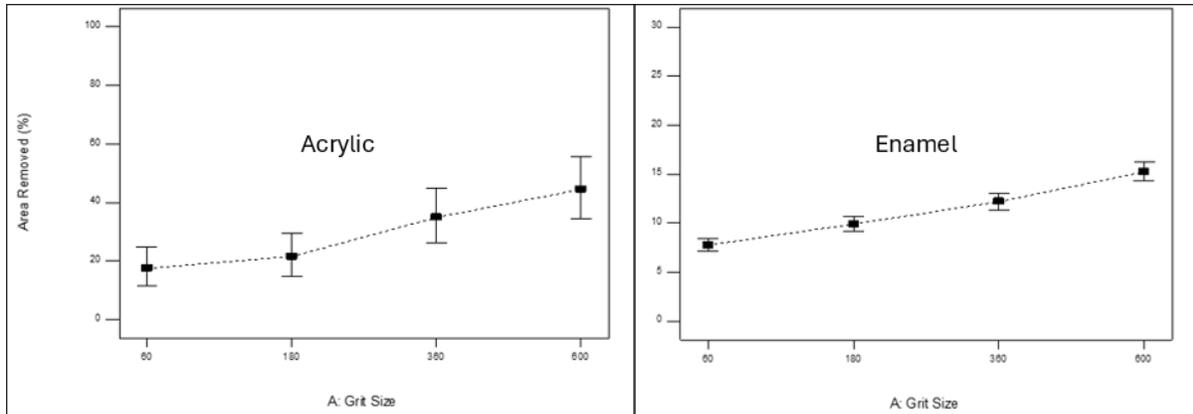


Figure 9. Model graph for the main effect of grit size for acrylic and enamel paint.

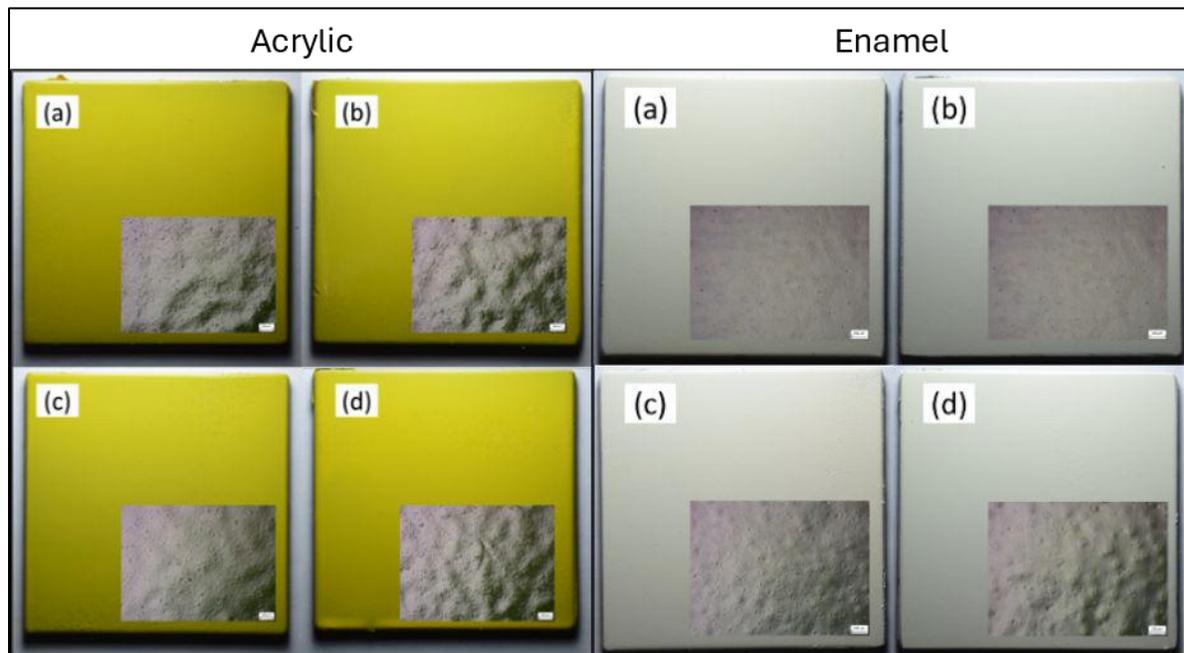


Figure 10. Visual and optical comparison of sprayed acrylic and enamel paint with primer applied using (a) 60, (b) 180, (c) 360, and (d) 600 sandpaper grit size

3.5 Effects of Application Method for Acrylic Paint

In terms of application method for acrylic paint, it was observed that the percent area removed on paint when applied through brushing (1B rating) is higher than through spraying (3B rating) (Figure 11). Moreover, paint samples applied through spraying had more uniform paint surface than those applied through brushing (Figure 12). This suggests that acrylic paint is better applied through spraying than brushing as it is also observed in similar studies.

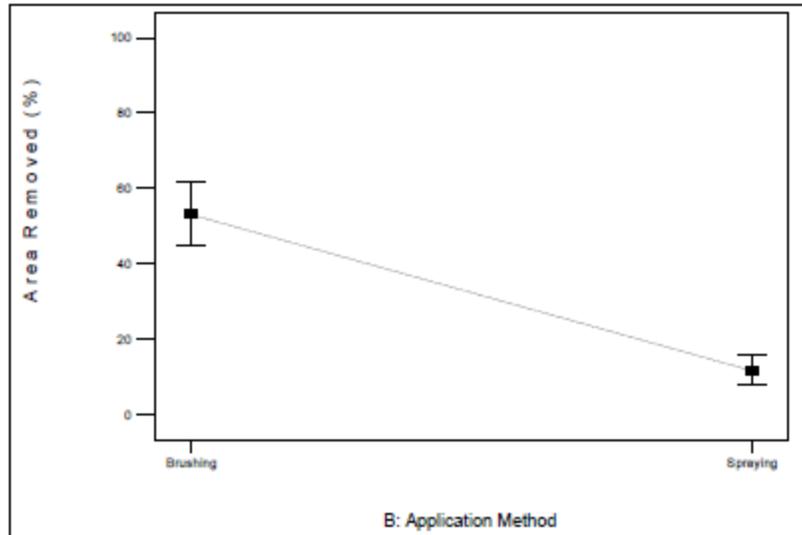


Figure 11. Model graph for the main effect of grit size for acrylic paint.

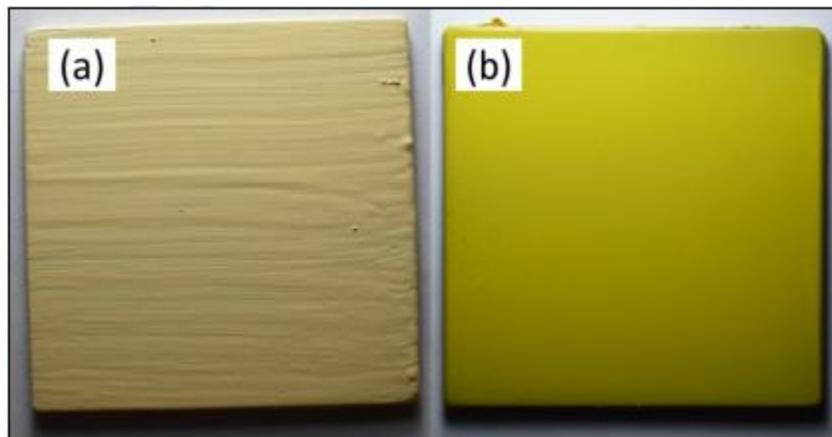


Figure 12. Visual comparison of acrylic paint with primer applied using (a) brushing, and (b) spraying

3.6 Effects of Primer Paint for Acrylic Paint

For the inclusion of primer paint for acrylic paint, the lowest predicted mean of percent area removed was observed for PT paint system (3B rating) while the highest was observed for TO paint system (1B rating) (Figure 13). Furthermore, the rating for PT was also better than SPT (2B rating). This means that the addition of primer paint before topcoat can improve paint adhesion for acrylic paint.

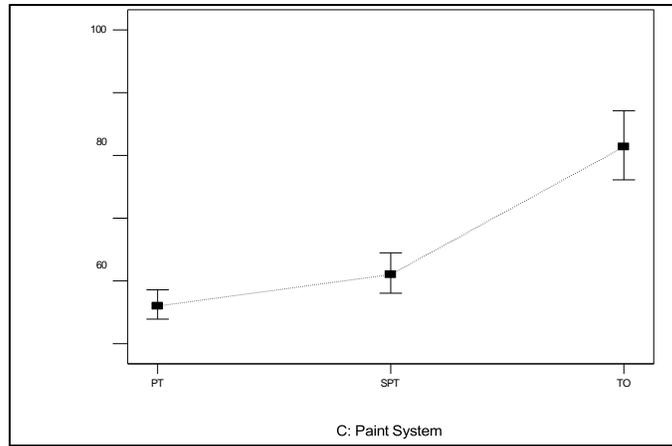


Figure 13. Model graph for the main effect of paint system for acrylic paint.

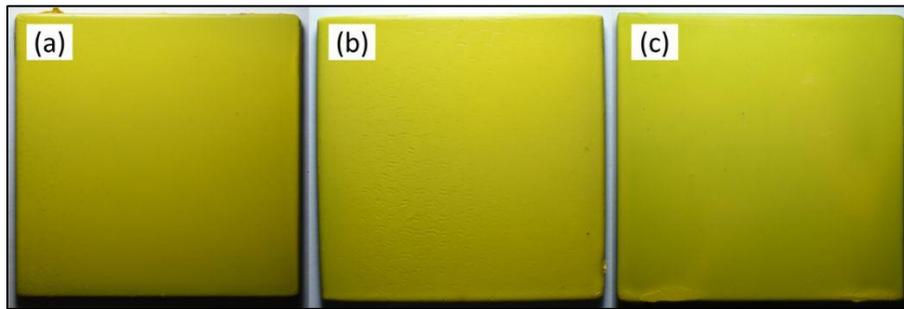


Figure 14. Visual comparison of acrylic paint applied (a) with primer, (b) with sanded

3.7 Interaction of Application Method and Primer Paint for Enamel Paint

As shown in Figure 15, applying enamel paint by spraying results to a lesser area removed than by brushing regardless of the paint system used. However, when applying by spraying, the results for PT and SPT paint systems are insignificantly different. This means that the two paint systems performed similarly in terms of adhesion. By visual inspection shown in Figure 16, no significant difference in appearance was observed between PT and SPT paint systems.

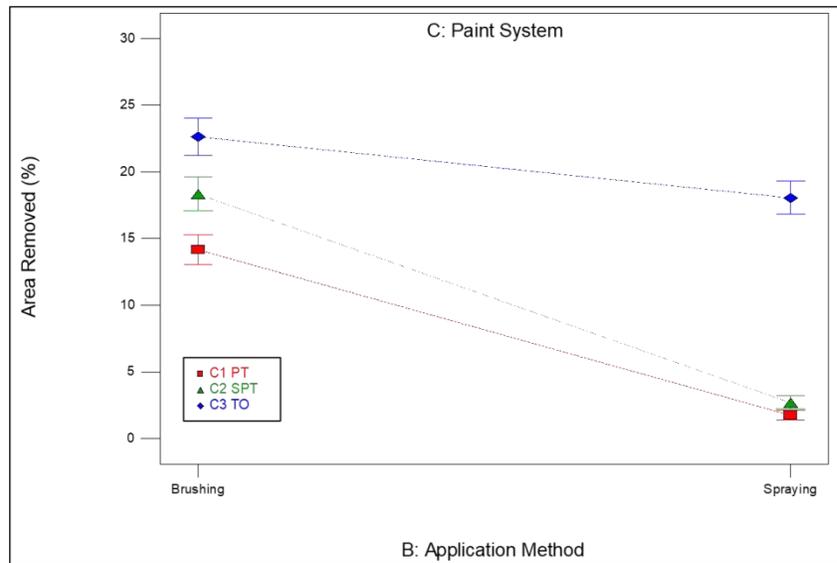


Figure 15. Model graph for the interaction of application method and paint system for enamel paint.

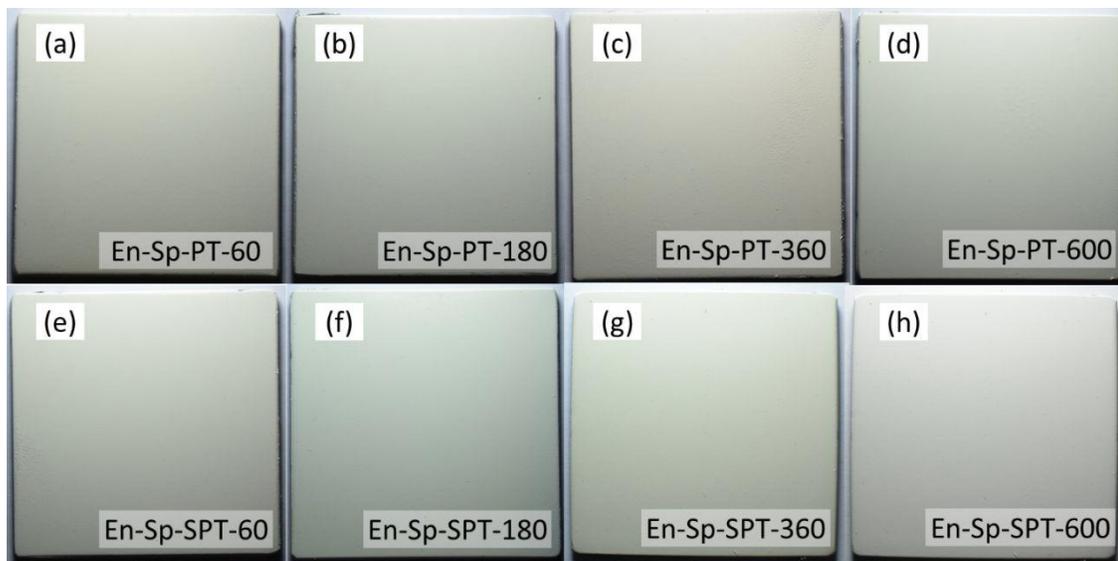


Figure 16. Visual comparison of sprayed enamel paint (a-d) with primer, and (e-h) with sanded primer

3.6 Numerical Optimization of Factors

Using numerical optimization of Design-Expert software, the combination of factors with highest desirability to minimize the percent area removed was sandpaper grit size of 60, spraying as application method, and PT (primer + topcoat) paint system. A sample was fabricated and tested to confirm the predicted mean of using the combination. The resulting percent area removed of 0.7052 validated the desirability of the combination, which ensures the best paint adhesion for acrylic paint and prevents premature failure due to poor adhesion.

IV. CONCLUSIONS

This study successfully evaluated the effects of surface roughness, application method, and inclusion of primer paint on the adhesion of acrylic and enamel paints on mild steel plates. All samples were coated under controlled conditions and tested using Tape Test method, with quantified results using ImageJ image processing software. The results showed that each of the three factors – sandpaper grit size, application method, and primer paint – significantly influenced the percentage of area removed during adhesion testing. Among the tested variables, coarser grit sandpaper (grit size 60) consistently resulted in lower percentage removed area, indicating stronger mechanical interlocking and improved adhesion. Spraying as application method produced more uniform paint layers and better adhesion than brushing. Additionally, the use of primer paints, particularly the primer + topcoat (PT) system, significantly enhanced adhesion compared to applying topcoat alone or over sanded primer.

Numerical optimization confirmed that the combination of 60 grit-size sandpaper, spraying method, and PT system yielded the highest adhesion performance, achieving a 5B classification – indicating no paint detachment after testing. This optimal combination is applicable for both acrylic and enamel paint types.

These findings emphasize the critical role of proper surface preparation in maximizing paint performance, particularly for agricultural machinery subjected to harsh environmental conditions. The methodology presented can serve as foundation to future studies involving alternative surface treatment, environmental exposure testing, or the use of advanced paint technologies to further improve long-term durability and corrosion protection.

V. ACKNOWLEDGEMENT

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