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Effect of Surface Roughness on Adhesion Strength and Corrosion Resistance of Silica-Epoxy Composite Coated Low Carbon Steel

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Abstract

Low-carbon steel is widely used in various industries but is susceptible to corrosion in aggressive environments, prompting this study on an epoxy-silica composite coating with variations in silica concentration (0-5 wt.%), sonication dispersion, and surface preparation (abrasive blast cleaning and power tool cleaning); the results showed that abrasive blast cleaning produced a surface roughness of 79 µm and superior adhesion strength (10.48 MPa) compared to power tool cleaning, with a perfect 5A rating in the x-cut tape test for all silica concentrations, while the highest adhesion strength of 14.33 MPa was achieved at 3 wt.% silica, and coating durability tests revealed the best performance exhibiting minimal corrosion propagation of only 0.55 mm after 72 hours at 5 wt.% silica in scratch tests using abrasive blast cleaning, underscoring the significant influence of surface preparation method on coating performance.

Keywords: *Epoxy-silica composite, corrosion resistance, surface preparation, adhesion strength, sonication*

1. INTRODUCTION

Low-carbon steel, often referred to as mild steel, constitutes the backbone of global industrial development, with annual production exceeding 1.8 billion tons [1]. Its unparalleled dominance in construction, automotive, and marine applications is attributed to a favorable combination of economical cost, ease of fabrication, and adequate mechanical strength [2]. Despite these advantages, a critical Achilles' heel remains: its pronounced susceptibility to corrosion, especially in aggressive environments such as seawater rich in chloride ions [2]. This degradation not only drastically shortens the material's service life but also elevates the risk of catastrophic structural failures, necessitating the development of robust, effective, and sustainable protective solutions.

Organic polymeric coatings, particularly those based on epoxy resins, are widely employed as primary protective barriers. Epoxy is favored for its strong adhesion, chemical resistance, and dimensional stability [3]. To further improve performance, composite coatings incorporating functional fillers such as silica (SiO_2) have attracted considerable interest. In this study, high-purity precipitated silica derived from quartz sand sourced from Kendawangan, West Kalimantan, is used. The silica was obtained through a series of steps, including roasting, hot-water dissolution, leaching, precipitation, and repeated hydrochloric acid washing. This silica composition test result

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confirmed that precipitated silica achieves a purity level of 99.99%, as can be seen in Table 1[4].

The incorporation of such silica into the epoxy matrix enhances barrier properties by creating a tortuous path that hinders the penetration of water, oxygen, and corrosive ions. Additionally, silica serves as a reinforcing phase, improving mechanical properties such as abrasion resistance and hardness [5].

Table 1. The chemical composition of silica precipitate

Compound	Content (wt.%)
SiO_2	99.99566
Al_2O_3	0.00088
Fe_2O_3	0.00034
TiO_2	0.00112
CaO	0.00012
MgO	0.00024
NaO	0.00088
LOI	0.00077

The performance of silica-epoxy composite coatings is highly dependent on two crucial factors: the uniformity of filler dispersion and the quality of substrate preparation. Silica particles, particularly at nano- and micro-scales, tend to agglomerate due to strong van der Waals forces, leading to defects that can become pathways for corrosive agents and points of stress concentration. Therefore, achieving a homogeneous dispersion is essential [6]. While various mechanical mixing methods are available, ultrasonication has been identified as a highly effective technique. It uses high-frequency sound waves to generate acoustic cavitation, producing intense local shear forces that break apart agglomerates and ensure even distribution within the epoxy matrix [7].

Equally important is the preparation of the steel substrate, as coating performance is fundamentally reliant on adhesion. Surface treatment methods such as abrasive blast cleaning and power tool cleaning are designed to remove contaminants like rust, mill scale, and old paint, while also imparting a specific surface roughness. Abrasive blast cleaning, which involves propelling abrasive media at high speed, typically produces a higher and more consistent surface profile compared to power tool techniques such as grinding or wire brushing [8]. The resulting surface topography enhances mechanical interlocking between the coating and substrate, significantly improving adhesion and long-term durability [9].

While the individual effects of silica reinforcement and surface preparation on coating performance have been examined separately, their combined influence, particularly the interaction between surface roughness and dispersion quality in relation to adhesion and corrosion resistance, remains insufficiently explored. This represents a significant research gap regarding the synergistic relationships among these critical parameters [10].

The present study aims to address this gap through a comprehensive investigation of epoxy-silica composite coatings applied to low-carbon steel substrates. The research systematically examines three key variables: silica concentration was varied from 0 to 5 wt.% to determine optimal loading levels; ultrasonication was employed as the dispersion method to ensure homogeneous distribution within the epoxy matrix; and a direct comparison was made between abrasive blast cleaning and power tool cleaning to evaluate their respective effects on surface roughness.

Through this integrated approach, the study seeks to identify the optimal conditions that synergistically enhance coating performance. The findings are expected to provide valuable practical insights for industrial applications in corrosive environments, particularly where both mechanical durability and long-term corrosion protection are essential requirements.

2. MATERIALS AND METHODS

In this experiment, a surface-tolerant epoxy resin was used as the primary matrix for the coating. The epoxy composite was modified by incorporating microsilica filler at a 99 wt% from Kendawangan quartz sand. To ensure homogeneous dispersion and deagglomeration of the filler within the epoxy matrix, the mixture was subjected to a sonication process. The resulting epoxy composite coating was then applied to a substrate of low-carbon steel, specifically AISI 1008 series, to evaluate its performance.

2.1 Materials

The coating was formulated using a commercial surface-tolerant epoxy system, specifically International Paint's RE 1553 (Part A) and RE 6529 (Part B). This two-component system was prepared by first mixing the base resin with a dedicated hardener at a fixed ratio of 6:1 (resin to hardener). To achieve an optimal application viscosity, the mixture was diluted with thinner, which was added at a concentration of 20% by volume of the total solution. Microsilica filler was subsequently incorporated into this epoxy blend to form a composite. The specific weight percentage (wt.%) of the microsilica filler used in this study is provided in Table 1.

The substrate selected for this investigation was low-carbon steel, conforming to the AISI 1008 series specification. The precise elemental composition of this steel substrate was quantitatively ascertained using OES (optical emission spectroscopy) to ensure material consistency and for subsequent corrosion performance analysis; the full OES results are detailed in Table 2.

The formulated epoxy composite coating was then uniformly applied to the prepared surface of this AISI 1008 steel substrate to evaluate its protective properties.

Table 2. Chemical composition of carbon steel using OES

Element	Content (wt.%)
Fe	99.54
C	0.052
Mn	0.187
N	0.048
Al	0.028
Fe	99.54
Cu	0.022
Te	0.035
Ni	0.015
Cr	0.011
W	0.013
V	0.0056
Co	0.0081
Sb	0.0077
Nb	0.0068
Bi	0.0035

The adhesive strength of the applied epoxy composite coating was quantitatively evaluated using a direct pull-off test according to a relevant standard (e.g., ASTM D4541 or ISO 4624). For this purpose, a dolly was affixed to the coated surface using a high-strength epoxy adhesive (araldite) and subjected to a perpendicular tensile force until failure.

Qualitative assessment of adhesion was further conducted via an X-cut tape test (e.g., ASTM D3359 or ISO 2409), utilizing a precision cutter and a specified pressure-sensitive tape to determine the coating's resistance to detachment from the substrate.

Furthermore, the coating's corrosion resistance and the durability of its adhesion in a hostile environment were investigated through a salt spray test (e.g., ASTM B117 or ISO 9227). A 5 wt% sodium chloride (NaCl) solution was prepared by dissolving 5 g of NaCl in 1000 mL of deionized water and was used to maintain a continuous corrosive fog within the testing chamber.

2.2 Methods

This study was conducted using a low-carbon steel plate as the primary substrate, prepared in three distinct dimensions: 10×10×3 mm for salt spray and adhesion testing and 1.5×1.5×3 mm for SEM-EDX characterization. Surface preparation was performed via two methods: power tool cleaning with a steel wire brush cup and abrasive blast cleaning using garnet abrasive. The resulting surface profile was measured using a Testex tape and an analog snap gauge to ensure preparation consistency.

An epoxy-silica composite coating was formulated through a sonication process to achieve optimal particle dispersion, followed by the addition of a hardener agent. The physical characteristics of the coating solution, including density and flow rate, were measured using a pycnometer and a flow cup viscometer.

Ambient conditions during coating application were monitored with a sling psychrometer, and the coating thickness was controlled using a manual film applicator and verified with a PosiTector 6000 coating thickness gauge.

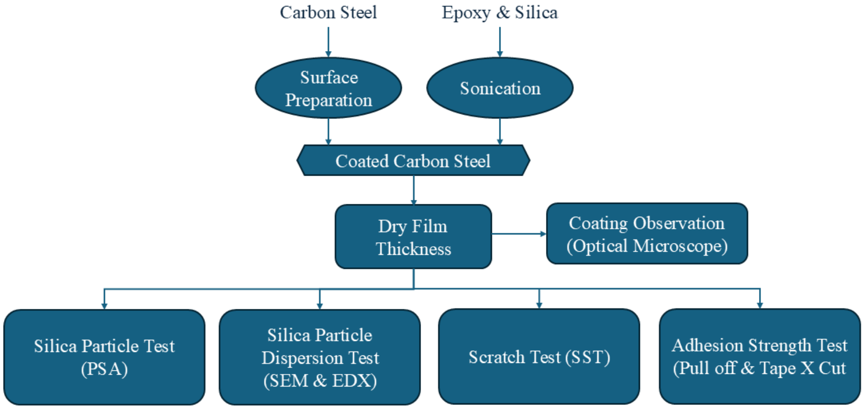


Figure 1. Research flowchart

2.3 Characterization

The characterization process in this study focused on analyzing the dispersion and distribution of silica within the epoxy matrix following the sonication process.

The particle size distribution of the silica within the epoxy composite was determined using a laser scattering particle size distribution analyzer (Horiba LA-960). The epoxy composite in liquid form was placed in a sample cell for characterization to evaluate the effectiveness of the sonication process in deagglomerating the silica particles.

The microstructure and elemental composition of the epoxy-silica composite were analyzed using a scanning electron microscope (JEOL JSM-IT200) equipped with an energy dispersive X-ray spectroscopy system. This technique provided high-resolution images of the surface morphology to visually assess the dispersion homogeneity of the silica filler. The integrated EDX system was used to perform quantitative elemental analysis and to map the distribution of silicon and oxygen, confirming the uniform distribution of silica particles within the epoxy polymer matrix.

3. RESULTS AND DISCUSSION

3.1 Visual Surface Observation

Visual assessment against SSPC-VIS 1 and SSPC-VIS 3 standards confirmed that both abrasive blast cleaning and power tool cleaning significantly improved the surface condition from an initial Rust Grade C.

Abrasive blast cleaning effectively produced a surface meeting the CSP-5 (white metal) standard. The process successfully removed all visible mill scale, rust, and old coatings, exposing a clean, profiled metallic substrate ideal for coating adhesion. This high level of cleanliness is attributed to the high kinetic energy of the abrasive particles.

In contrast, power tool cleaning achieved the SSPC C SP3 PWB standard. While this method also removed the majority of contaminants, minimal residues remained on the surface. The results demonstrate that abrasive blast cleaning provides a superior surface profile and cleanliness compared to power tool cleaning, which leaves slight staining.

3.2 Surface Roughness After Preparation

Surface roughness measurements were conducted to verify the consistency of the surface profile generated by the two preparation methods. The results, presented in Table 3, show a distinct difference between the techniques.

Abrasive blast cleaning resulted in a high average surface roughness of 79.4 µm, with a standard deviation of approximately 6.4. This value falls within the typical range reported in the literature for garnet abrasives (40-125 µm) and is attributed to the aggressive impact of the abrasive particles on the steel substrate [11].

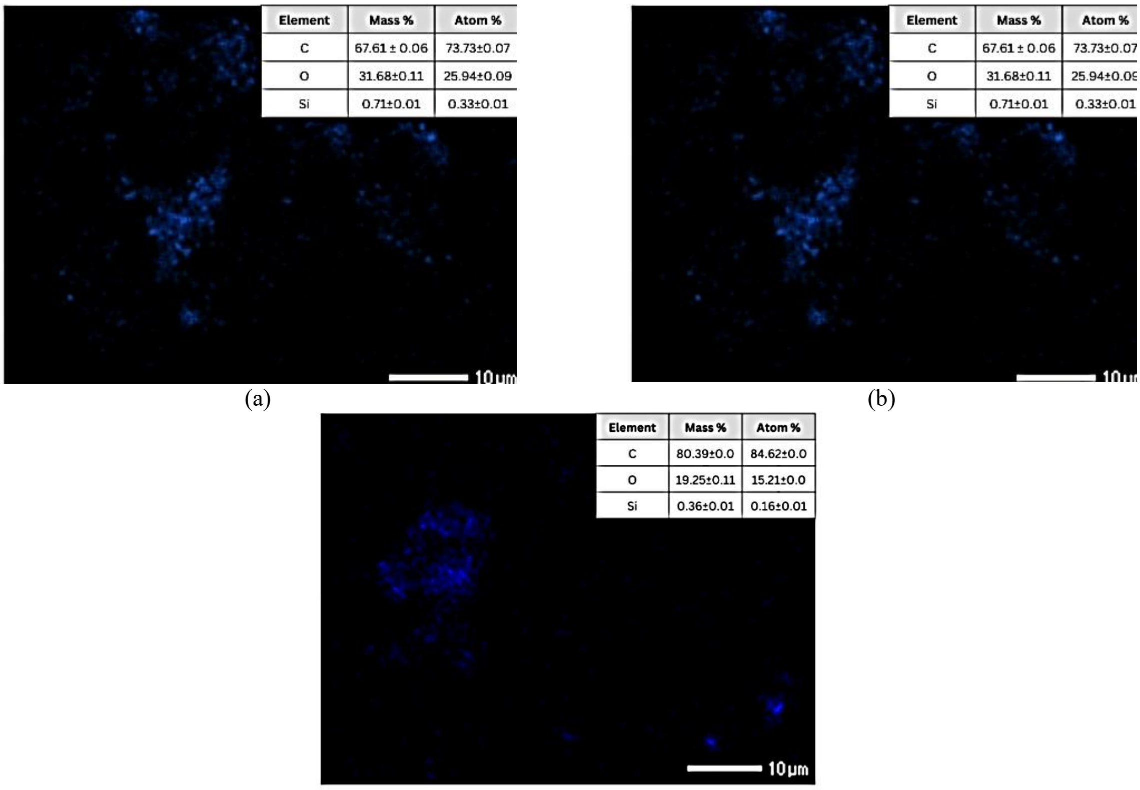
In contrast, power tool cleaning yielded a significantly lower average roughness of 27.2 µm with a standard deviation of about 3.4. The mechanical action of the steel wire brush cup not only cleans the surface but also has a polishing effect, resulting in a smoother final profile. This clear distinction highlights that the choice of preparation method directly determines the resultant surface topography, a critical factor for coating adhesion.

Table 3. Surface roughness value after surface preparation

Surface Preparation Method	Sample	Roughness (µm)	Average (µm)
Abrasive Blast Cleaning	1	75	79.4
	2	80	
	3	74	
	4	90	
	5	78	
Power Tool Cleaning	1	30	27.2
	2	29	
	3	23	
	4	30	
	5	24	

3.3 Silica Dispersion and Particle Size Analysis

SEM-EDX mapping analysis was performed to evaluate the dispersion quality of silica particles within the epoxy matrix across different filler loadings. Figures 2(a)-2(c) reveal that at low silica concentrations (0.3-0.75 wt.%), the filler particles were not uniformly distributed and tended to form agglomerates. The significant discrepancy between the added silica and the EDX-measured composition confirmed this poor dispersion, a phenomenon previously reported [12]. In contrast, Figures 3(a) and 3(b) show that samples with 1 and 3 wt.% loadings exhibited superior dispersion homogeneity, with EDX results closely matching the intended concentrations. However, at the highest loading of 5 wt.% (Fig. 3(c)), a degradation in dispersion quality was observed, indicated by a lower EDX-measured value, suggesting particle re-agglomeration due to dominant van der Waals forces and exceeding the optimal capacity for the sonication energy [13].



Element	Mass %	Atom %
C	67.61 ± 0.06	73.73±0.07
O	31.68±0.11	25.94±0.09
Si	0.71±0.01	0.33±0.01

(a)

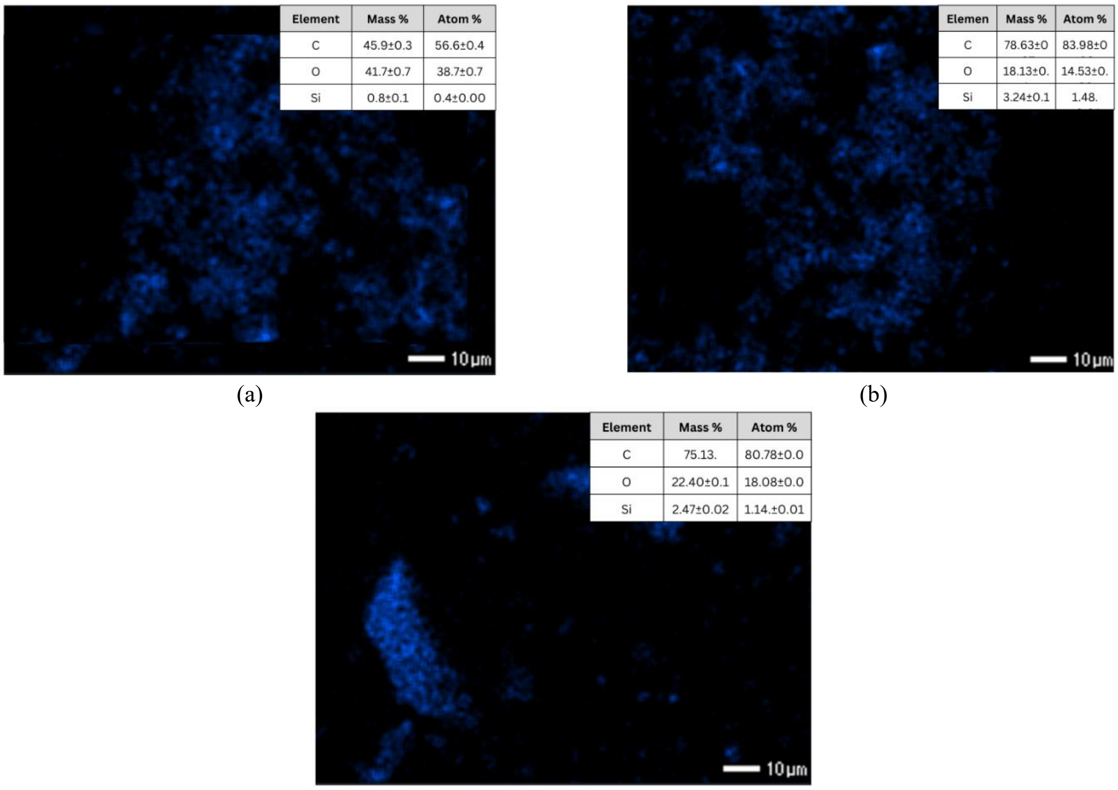
Element	Mass %	Atom %
C	67.61 ± 0.06	73.73±0.07
O	31.68±0.11	25.94±0.0
Si	0.71±0.01	0.33±0.01

(b)

Element	Mass %	Atom %
C	80.39±0.0	84.62±0.0
O	19.25±0.11	15.21±0.0
Si	0.36±0.01	0.16±0.01

(c)

Figure 2. SEM and EDX analysis results with the addition of silica filler (wt.%): (a) 0.3, (b) 0.5, (c) 0.75



Element	Mass %	Atom %
C	45.9±0.3	56.6±0.4
O	41.7±0.7	38.7±0.7
Si	0.8±0.1	0.4±0.00

(a)

Elemen	Mass %	Atom %
C	78.63±0	83.98±0
O	18.13±0.	14.53±0.
Si	3.24±0.1	1.48.

(b)

Element	Mass %	Atom %
C	75.13.	80.78±0.0
O	22.40±0.1	18.08±0.0
Si	2.47±0.02	1.14.±0.01

(c)

Figure 3. SEM and EDX analysis results with the addition of silica filler (wt.%): (a) 1, (b) 3, (c) 5

Particle size analysis revealed that sonication effectively reduced the initial silica size (~44 µm) to a range of 4.12-13.86 µm. The smallest average particle size (4.12 µm) was achieved at 1 wt.% loading, indicating optimal sonication efficiency where particle concentration allowed for effective energy transfer and deagglomeration without causing overcrowding. At lower concentrations (0.3-0.75 wt.%),

The larger particle sizes suggest suboptimal utilization of sonication energy due to an insufficient number of particle collisions [14].

Conversely, at higher loadings (3-5 wt.%), the observed increase in particle size is attributed to overloading, where particle screening effects and increased viscosity hinder effective sonication and promote re-agglomeration [13].

3.4 Flow Rate and Density of Epoxy Composite

The incorporation of silica filler significantly influenced the physical properties of the epoxy composite. As shown in Tables 4 and 5, increasing the silica content from 0 to 5 wt.% resulted in a consistent rise in density, from 1.091 g/mL to 1.1500 g/mL. This linear increase is attributed to the higher intrinsic density of silica particles compared to the epoxy matrix and their effective role in filling the free volume within the polymer structure [15].

Table 4. Density of epoxy composite solution

Silica Parameters (wt.%)	Density (g/mL)
0	1.091
0.30	1.096
0.5	1.099
0.75	1.008
1	1.1120
3	1.1372
5	1.1500

Concurrently, the flow rate of the composite decreased substantially from 0.36 cm/s for the neat epoxy to 0.07 cm/s for the 5 wt.% formulation. This inverse relationship between filler loading and flow rate demonstrates the increased viscosity and internal resistance to flow caused by the silica particles, which form a network that hinders the movement of the polymer chains [16]. Despite this reduction, the flow rates remained within a workable range for coating applications. The controlled increase in density and the corresponding adjustment in flow rate within the 1-5 wt.% range are considered beneficial for enhancing mechanical and barrier properties without compromising processability [17].

Table 5. Flow rate of epoxy composite solution

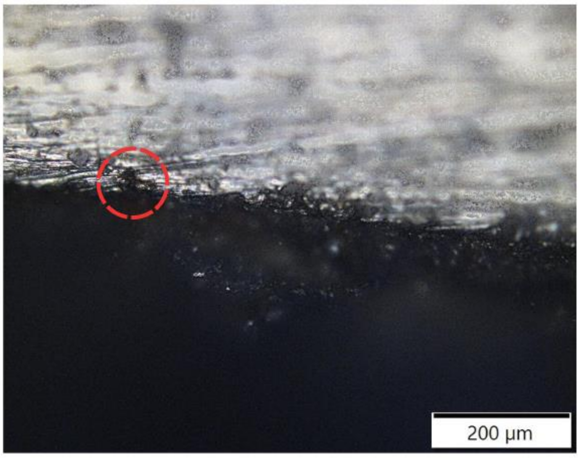
Silica Addition	Time (Second)	Height (cm)	FlowRate (cm/second)
0	32	11.5	0.36
0.3	45	11.5	0.26
0.5	72	11.5	0.16
0.75	117	11.5	0.10
1	130	11.5	0.09
3	147	11.5	0.08
5	160	11.5	0.07

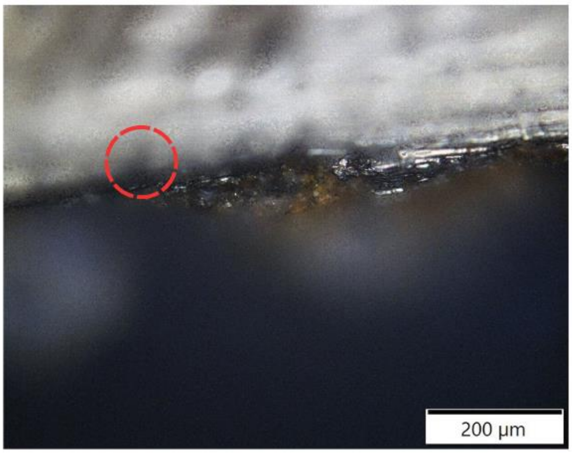
3.5 Coating Layer Analysis

Optical microscopy analysis revealed a significant influence of the surface preparation method on the coating morphology and integrity. Coatings applied on abrasively blast-cleaned substrates. Figure 4 exhibited a uniform, void-free epoxy composite layer with a consistent thickness. In contrast, coatings on power tool-cleaned substrates showed the presence of residual oxide layers, indicating the method's inability to completely remove surface contaminants [13].

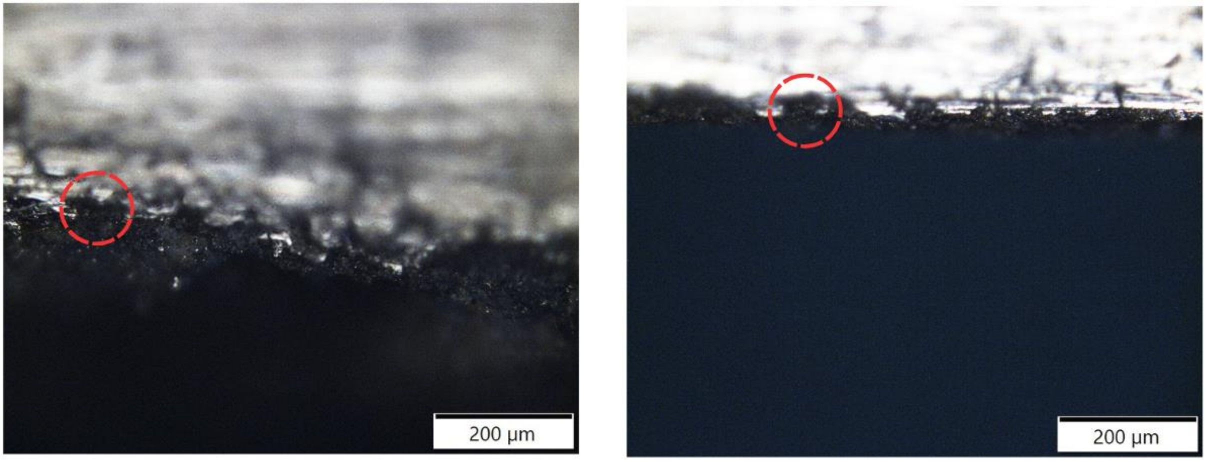
A key distinction was the presence of mechanical interlocking, visible in all samples on blast-cleaned surfaces (red circles, Fig. 4). This anchoring mechanism, resulting from the higher surface roughness, enhances coating adhesion [18]. This feature was absent in all coatings on power tool-cleaned surfaces (Fig. 5), which only provided cleaning without creating a significant anchoring profile [19].

The superior surface profile generated by abrasive blast cleaning is therefore concluded to be critical for achieving optimal coating adhesion and anticipated corrosion resistance.





(a) (b)



(c) (d)

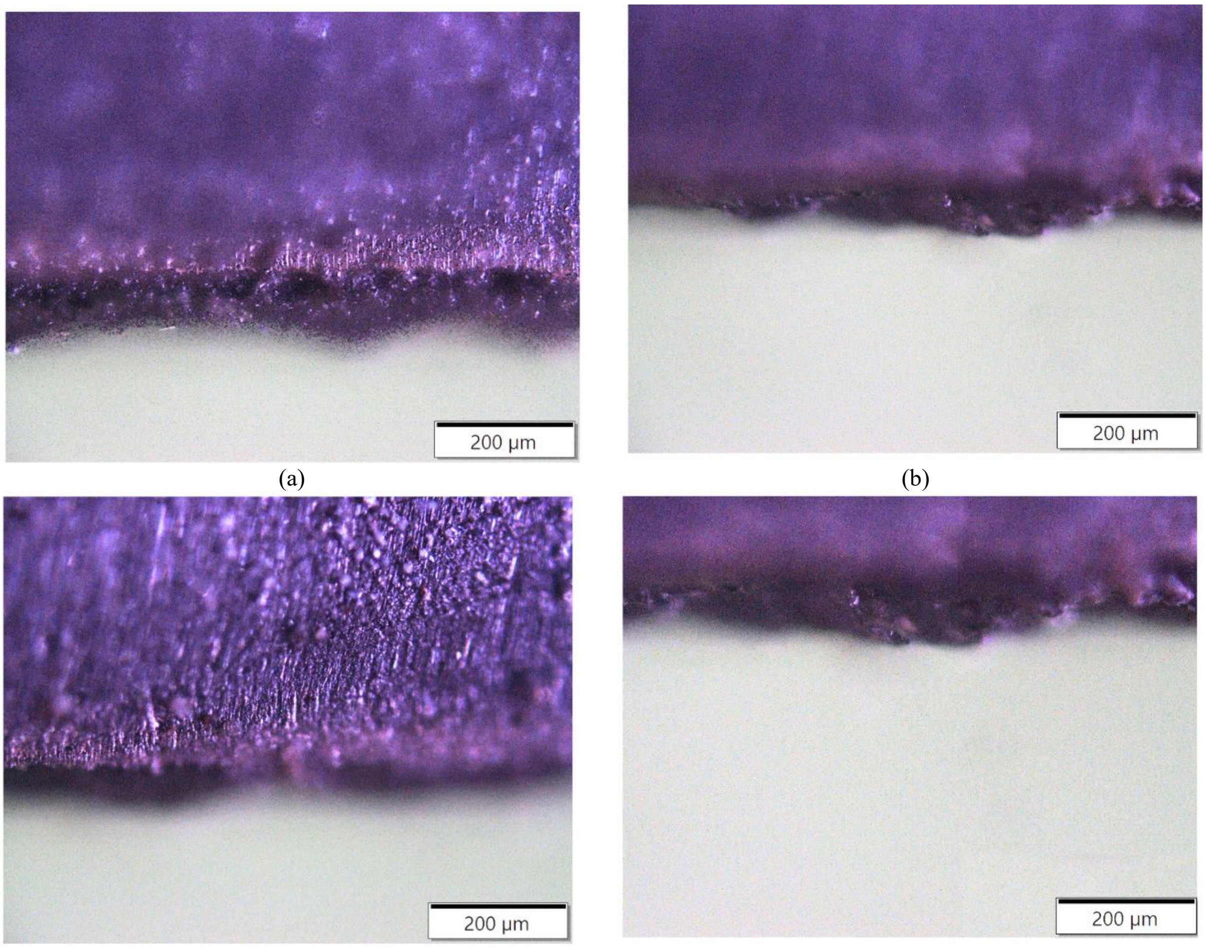
Figure 4. OM results on epoxy coatings using the abrasive blast cleaning method with the addition of silica filler (wt.%): (a) 0, (b)1, (c). 3 and (d) 5

3.5 Coating Thickness Analysis

The DFT (dry film thickness) of the cured epoxy coatings was measured at multiple points across all samples. Coatings applied on abrasively blast-cleaned substrates consistently yielded higher average thicknesses, ranging from approximately 170-227 µm across different silica loadings. In contrast, coatings on power tool-cleaned surfaces showed lower average thicknesses, ranging from about 104-164 µm [20]. This variation is attributed to the different surface profiles created by the preparation techniques. The rougher profile from abrasive blasting retained a thicker coating layer. Furthermore, for both methods, an increase in silica filler content generally resulted in a trend towards greater coating thickness, which aligns with the previously observed increase in composite density and viscosity [21]. Despite the variations, all measured thicknesses were within a range considered acceptable for protective coating applications [22].

3.6 Adhesion Strength Analysis

The adhesion of the epoxy-silica composite coatings was evaluated using two complementary methods: a qualitative tape test (x-cut) and a quantitative pull-off test. The results from both tests are detailed in the following subsections to provide a comprehensive analysis of the coating-substrate bond strength.



(a) (b)

(c) (d)

Figure 5. OM results on epoxy coatings using the power tool cleaning method with the addition of silica filler (wt.%): (a) 0, (b)1, (c). 3 and (d) 5

3.7 Tape X-Cut Test Results

The qualitative adhesion of the epoxy-silica composite coatings was evaluated using the Tape X-Cut test according to ASTM D3359. The results, detailed in Table 6, demonstrate a clear correlation between surface preparation, silica content, and adhesion performance.

Coatings applied on abrasively blast-cleaned substrates consistently achieved a perfect 5A rating (no peeling) across all silica loadings (0 to 5 wt.%). This superior performance is attributed to the high surface roughness generated by this method, which provides excellent mechanical interlocking for the coating [23].

In contrast, coatings on power tool-cleaned surfaces showed more variable results. While the 0.5 wt.% and 0.75 wt.% silica samples achieved a 5A rating, the unfilled (0 wt.%) and 0.3 wt.% samples showed lower adhesion with ratings of 4A and 3A, respectively. This indicates that the incorporation of silica filler above 0.5 wt.% significantly enhances adhesion strength [24], likely by improving the composite toughness and the interfacial bond between the polymer matrix and the substrate [25]. This effect compensates for the inherently lower surface profile provided by the power tool cleaning method.

3.8 Pul Off Test Results

Quantitative adhesion strength was evaluated using the pull-off test, revealing a significant influence of surface preparation and silica content. As shown in Figure 6, coatings applied on abrasively blast-cleaned substrates demonstrated a higher average adhesion strength (10.48 MPa) compared to those on power tool-cleaned surfaces (6.16 MPa) [26]. This is directly correlated with the superior surface roughness (79.4 µm) provided by abrasive blasting, which enhances mechanical interlocking [10].

Table 6. X-cut test result

Surface Preparation Methods	Dosage of Silica (wt.%)	antitative Scale of Adhesion Strength
Abrasive blast cleaning	0	5A
	1	5A
	3	5A
	5	5A
Power tool cleaning	0	4A
	0.3	3A

0.5	5A
0.75	5A

The effect of silica filler was distinct for each preparation method. For power tool cleaning, adhesion increased drastically to 9.33 MPa at 0.5 wt.% silica, demonstrating the filler's role in enhancing bond strength. For abrasive blast cleaning, the optimal adhesion strength of 14.33 MPa was achieved at 3 wt.% silica.

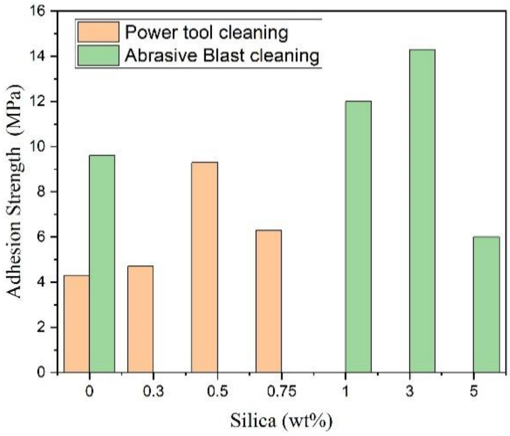


Figure 6. Comparison chart of adhesion strength of abrasive blast cleaning and power tool cleaning on silica materials

However, a further increase to 5 wt.% silica caused adhesion to drop to 6 MPa, likely due to filler agglomeration and a non-ideal, excessive coating thickness, which can lead to higher internal stresses [27]. Failure mode analysis showed a predominance of adhesive failure (60-90%), indicating that the interface bond was stronger than the internal strength of the coating itself in most cases.

3.9 Coating Corrosion Resistance

The corrosion resistance of the coatings was evaluated using a scratch test, where an X-shaped scribe was made on the coating, and the sample was exposed to a 5% NaCl salt spray for 72 hours. The creepage, or under-film corrosion, from the scribe was measured periodically.

The results, detailed in Figs. 7 and 8, demonstrate a clear trend: coatings applied on abrasively blast-cleaned substrates (Fig. 8) exhibited significantly lower creepage and higher rating numbers than those on power tool-cleaned surfaces (Fig. 7) for all silica loadings [28].

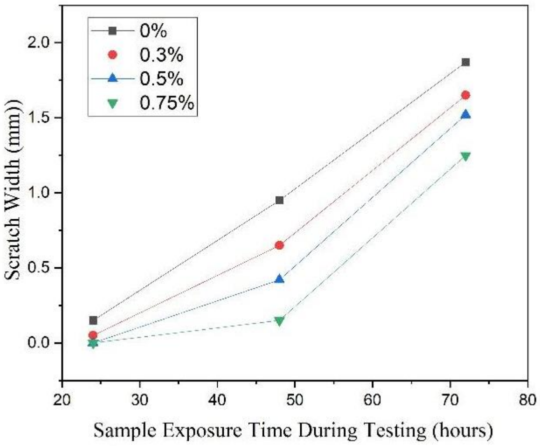


Figure 7. Comparison chart of pattern width vs exposure time for each addition of silica using the power tool cleaning method

This confirms the dominant role of surface preparation, where the superior profile from abrasive blasting provides a more effective barrier against corrosion undercutting [29].

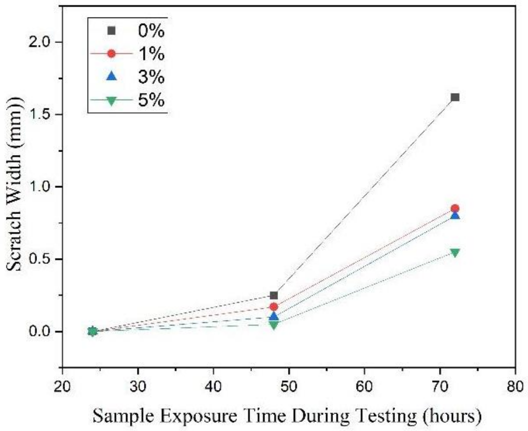


Figure 8. Comparison chart of pattern width versus exposure time for each addition of silica using abrasive blast cleaning

Furthermore, within each preparation method, the addition of silica filler consistently improved corrosion resistance. For power tool cleaning, the 0.75 wt.% silica sample showed the best performance (1.55 mm creepage after 72h). For abrasive blast cleaning, the 5 wt.% silica sample provided the optimal protection, with the lowest final creepage of 0.55 mm. This indicates that silica enhances the coating's barrier properties, but its effectiveness is maximized when combined with an appropriate surface profile [30].

The effect of surface roughness is evident when comparing power tool cleaning and abrasive blast cleaning samples. Power tool cleaning shows greater blister widening over time due to under film corrosion, where an oxide layer forms between the coating and substrate. This layer reduces adhesion strength and accelerates corrosion, consistent with previous studies [29].

4 CONCLUSION

Based on the findings of this study, it is concluded that the surface roughness of low carbon steel, dictated by the preparation method, is a fundamental factor controlling the adhesion performance that can contribute to the corrosion performance of silica-epoxy composite coatings. Abrasive blast cleaning, which produced a superior surface roughness (79 µm), was proven to be the critical enabler for both perfect adhesion (5A) using the tape x cut test and the pull off test (10.48 MPa), which increase 41% of adhesion strength compared to the average of power tool cleaning. The optimal adhesive strength (14.33 MPa) was achieved with 3 wt.% silica. Notably, the highest corrosion resistance, evidenced by a minimal creepage of 0.55 mm after 72 hours, was attained with 5 wt.% silica on this properly roughened surface, underscoring that optimal corrosion protection is achieved through the synergy of adequate filler concentration and a substrate roughness that ensures flawless coating adhesion.

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REFERENCES

[1] P. Refait, A.-M. Grolleau, M. Jeannin, C. Rémazeilles, and R. Sabot, "Corrosion of carbon steel in marine environments: Role of the corrosion product layer," *Corrosion and Materials Degradation*, vol. 1, no. 1, pp. 198-218, 2020. DOI: 10.3390/cmd1010010

[2] M. F. Álvarez, F. Velasco, A. Bautista, F. C. M. Lobo, E. M. Fernandes, and R. L. Reis, "Manufacturing and characterization of coatings from polyamide powders functionalized with nanosilica," *Polymers*, vol. 12, no. 10, p. 2298, 2020. DOI: 10.3390/polym12102298.

[3] A. Szewczak and M. Szeląg, "Physico-mechanical and rheological properties of epoxy adhesives modified by microsilica and sonication process," *Materials*, vol. 13, no. 23, p. 5310, 2020. DOI: 10.3390/ma13235310.

[4] A. B. Prasetyo, M. Handayani, E. Sulistiyo, F. Firdiyono, E. Febriana, W. Mayangsari, S. Wahyuningsih, E. Pramono, A Maksum, R. Riastuti, and J. W. Soedarsono, "Fabrication of high-purity silica precipitates from quartz sand toward photovoltaic application," *Journal of Ceramic Processing Research*, vol. 24, no. 1, pp. 103-110, 2023. DOI: 10.36410/jcpr.2023.24.1.103.

[5] A. A. Khan, A. Khan, Z. Zafar, I. Ahmad, and B. Islam, "Corrosion protection of aluminum alloy 7075 using functionalized micro-silica-based epoxy coatings," *Materials Research Express*, vol. 10, no. 4, p. 45301, 2023. DOI: 10.1088/2053-1591/acc6b5.

[6] A. Guzanová, J. Brezinová, D. Draganovská, and F. Jaš, "A study of the effect of surface pre-treatment on the adhesion of coatings," *Journal of Adhesion Science and Technology*, vol. 28, no. 17, pp. 1754-1771, 2014. DOI: 10.1080/01694243.2014.920762.

[7] M. K. Schäfer, "Ultrasonic mixing head for resin transfer molding: The interaction between sonication, process characteristics and resin system properties," Universität München, 2018.

[8] M. Brogly, "Forces involved in adhesion," *in Handbook of Adhesion Technology*, L. F. M. da Silva, A. Öchsner, and R. D. Adams, Eds., Cham: Springer International Publishing, pp. 1-28, 2017. DOI: 10.1007/978-3-319-42087-5_3-2.

[9] A. Rudawska, I. Danczak, M. Müller, and P. Valasek, "The effect of sandblasting on surface properties for adhesion," *International Journal of Adhesion and Adhesives*, vol. 70, pp. 176-190, 2016. DOI: 10.1016/j.ijadhadh.2016.06.010.

[10] W. Pathanatecha, "A study of various parameters affecting adhesion of coatings to metal substrates," 2019. [Online]. Available: https://api.semanticscholar.org/CorpusID:215762179

[11] M. A. Iglesias-Campos, "Effects of mechanical cleaning by manual brushing and abrasive blasting on lime render coatings on architectural heritage," *Materiales de Construcción*, vol. 64, no. 316, p. e039, 2014. DOI: 10.3989/mc.2014.08313.

[12] R. Wang, C. Zhang, and W. Liu, "Compatibility and anti-oxidation properties of study on liquid oxygen

compatibility with nano-modified epoxy composites," *Polymers and Polymer Composites*, vol. 19, no. 4-5, pp. 351-356, 2011. DOI: 10.1177/0967391111019004-515.

[13] M. F. Uddin and C. T. Sun, "Improved dispersion and mechanical properties of hybrid nanocomposites," *Composites Science and Technology*, vol. 70, no. 2, pp. 223-230, 2010. DOI: 10.1016/j.compscitech.2009.09.017.

[14] B. B. Johnsen, T. R. Fromyr, T. Thorvaldsen, and T. Olsen, "Preparation and characterization of epoxy/alumina polymer nanocomposites," *Composite Interfaces*, vol. 20, no. 9, pp. 721-740, 2013. DOI: 10.1080/15685543.2013.815603.

[15] R. J. Ghayyib, A. J. Salman, Z. F. Jawad, and Z. S. Al-Khafaji, "Effect of silica-based wastes on wear rate and hardness properties of epoxy composites as a construction material*," Key Engineering Materials*, vol. 895, pp. 31-40, 2021. DOI: 10.4028/www.scientific.net/KEM.895.31.

[16] R. Babba, K. Hebbache, A. Douadi, M. Boutlikht, R. Hammouche, S. Dahmani, G. D. Serroni and L. Morreti, "Impact of silica sand on mechanical properties of epoxy resin composites and their application in CFRP-concrete bonding," *Applied Sciences*, vol. 14, no. 15, p. 6599, 2024. DOI: 10.3390/app14156599.

[17] J. Sroka, A. Rybak, R. Sekula, and M. Sitarz, "An investigation into the influence of filler silanization conditions on mechanical and thermal parameters of epoxy resin-fly ash composites," *Journal of Polymers and the Environment*, vol. 24, no. 4, pp. 298-308, 2016. DOI: 10.1007/s10924-016-0773-8.

[18] C. Li, X. Jia, S. Wu, F. Li, X. Wang, and Y. Ren, "The removal mechanism considering the shape and size of abrasive particles in wet blast cleaning of paint," *Sustainability*, vol. 14, no. 21, p. 14289, 2022. DOI: 10.3390/su142114289.

[19] A. R. Safin, R. R. Khusnutdinov, and A. M. Kopylov, "The method topological optimization for design linear electric machines," in *2019 International Science and Technology Conference "EastConf,"* pp. 1-6, 2019. DOI: 10.1109/EastConf.2019.8725379.

[20] S. Luangkularb, S. Prombanpong, and V. Tangwarodomnukun, "Material consumption and dry film thickness in spray coating process," *Procedia CIRP*, vol. 17, pp. 789-794, 2014. DOI: 10.1016/j.procir.2014.02.046.

[21] S. R. Harisha, S. Sharma, U. A. Kini, and M. C. G. Shankar, "Study on spheroidization and related heat treatments of medium carbon alloy steels," *MATEC Web of Conferences*, vol. 144, p. 02008, 2018. DOI: 10.1051/matecconf/201714402008.

[22] S. Henkel, F. Beyrau, Y. Hardalupas, and A. M. K. P. Taylor, "Novel method for the measurement of liquid film thickness during fuel spray impingement on surfaces," *Optics Express*, vol. 24, no. 3, p. 2542, 2016. DOI: 10.1364/OE.24.002542.

[23] A. Kim, S. Kainuma, and M. Yang, "Surface characteristics and corrosion behavior of carbon steel treated by abrasive blasting," *Metals*, vol. 11, no. 12, p. 2065, 2021. DOI: 10.3390/met11122065.

[24] D. Schaubroeck, "Surface modifications of epoxy resins to improve the adhesion towards electroless deposited copper," Ghent University, 2015.

[25] A. J. Kinloch, J. H. Lee, A. C. Taylor, S. Sprenger, C. Eger, and D. Egan, "Toughening structural adhesives via nano- and micro-phase inclusions," *The Journal of Adhesion*, vol. 79, no. 8-9, pp. 867-873, 2003. DOI: 10.1080/00218460309551.

[26] Z. Zhang, Y. Wang, J. Lin, and D. Wang, "Study on factors influencing film formation of grease and calculation model for grease film thickness," *Lubricants*, vol. 10, no. 6, p. 123, 2022. DOI: 10.3390/lubricants10060123.

[27] M. A. Deyab, B. El Bali, Q. Mohsen, and R. Essehli, "Design new epoxy nanocomposite coatings based on metal vanadium oxy-phosphate M0.5VOPO4 for anti-corrosion applications," *Scientific Reports*, vol. 11, no. 1, p. 8182, 2021. DOI: 10.1038/s41598-021-87567-3.

[28] Sheetal, B. Chugh, S. Thakur, B. Pani, and A. K. Singh, "Fundamentals of corrosion chemistry," 2021, pp. 21-36. DOI: 10.1021/bk-2021-1403.ch002.

[29] M. Niknahad, S. Moradian, and S. M. Mirabedini, "The adhesion properties and corrosion performance of differently pretreated epoxy coatings on an aluminium alloy," *Corrosion Science*, vol. 52, no. 6, pp. 1948–1957, Jun. 2010, doi: 10.1016/j.corsci.2010.02.014.

[30] J. Wang, "Application and performance study of protective coatings in corrosion

resistance on industrial equipment surfaces," J*ournal of protective coatings & linings*, vol. 42, no. 4, pp. 57–73, 2025, [Online]. Available: https://paintsquare.com/jpcl/articles/2025/4245773.pdf