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Corrosion and Wear Rate Analysis of SS304 Stainless Steel with Composite Coating Variations: Aluminum/Silicon Carbide/Epoxy and Titanium Dioxide/Silicon Carbide/Epoxy

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Abstract

The palm oil industry presents significant challenges to material durability due to its corrosive and abrasive environment, particularly affecting components such as screw conveyors made from SS304 stainless steel. This study aims to analyze the influence of composite coating variations based on epoxy resin with the addition of aluminum (Al), silicon carbide (SiC), and titanium dioxide (TiO_2) on the corrosion and wear rates of SS304 in an H_2SO_4 medium. The methods employed include corrosion testing using the weight loss method in accordance with ASTM G31-72, and wear testing using the Ogoshi method following ASTM G99. Four specimen variations were evaluated: uncoated (Raw), pure epoxy, epoxy–Al–SiC (A), and epoxy–TiO_2–SiC (B).The results indicate that Specimen B exhibited the best corrosion resistance, with the lowest corrosion rate of 0.00798 mm/year, while Specimen A demonstrated the highest wear resistance, with a wear rate of 0.00042 $mm^3/kg \cdot m$. The pure epoxy specimen showed the poorest performance in both aspects. These findings confirm that the incorporation of reinforcing particles into the epoxy matrix plays a significant role in enhancing corrosion and wear resistance, thereby contributing to extended service life and improved equipment efficiency in extreme industrial environments.

Keywords: *epoxy; wear; corrosion; silica carbide; titanium dioxide*

Abstrak

Industri kelapa sawit menghadirkan tantangan serius terhadap keawetan material akibat lingkungan yang korosif dan abrasif, terutama pada komponen seperti screw conveyor berbahan baja tahan karat SS304. Penelitian ini bertujuan untuk menganalisis pengaruh variasi komposit coating berbasis epoxy resin dengan tambahan aluminium (Al), silika karbida (SiC), dan titanium dioksida (TiO_2) terhadap laju korosi dan keausan SS304 dalam media H_2SO_4. Metode yang digunakan meliputi uji korosi dengan metode weight loss mengacu pada ASTM G31-72 dan uji keausan dengan metode Ogoshi sesuai ASTM G99. Empat variasi spesimen diuji: tanpa coating (Raw), epoxy murni, epoxy–Al–SiC (A), dan epoxy–TiO_2–SiC (B). Hasil menunjukkan bahwa spesimen B memberikan ketahanan korosi terbaik dengan laju korosi terendah sebesar 0.00798 mm/tahun, sementara spesimen A menunjukkan ketahanan keausan tertinggi dengan laju keausan 0.00042 $mm^3/kg \cdot m$. Spesimen epoxy murni menunjukkan performa terburuk dalam kedua aspek. Temuan ini menegaskan bahwa kombinasi partikel penguat dalam epoxy berperan signifikan dalam meningkatkan ketahanan korosi dan aus, sehingga dapat memperpanjang umur pakai dan efisiensi peralatan dalam lingkungan industri yang ekstrem.

Kata kunci: epoxy; keausan; korosi; silika karbida; titanium dioksida

1. Introduction

Indonesia is one of the largest palm oil-producing countries in the world, with a significant contribution to the needs of the global market. The rapid growth of the palm oil industry has led to an increase in the need for efficiency and reliability of production systems, especially related to mechanical processes. Here, the screw conveyor is one of the important components in the palm oil processing equipment series. This device moves fresh fruit bunches (FFB), pulp, and other solid waste to various stages of the production process, such as sterilization, pressing, and extraction [1]. If the screw conveyor malfunctions, it will disrupt the production process flow, reducing the plant's output capacity and operational efficiency. However, the operating environment of palm oil mills is aggressive because of exposure to Free Fatty Acids (FFAs) and other corrosive chemical compounds that can damage metal surfaces, including SS304 stainless steel, a commonly used material as the base material for screw conveyors[2]. Although SS304 is known to have outstanding corrosion resistance, long-term exposure to acidic environments, high temperatures, and repeated mechanical friction makes this material vulnerable to wear and corrosion. In the long run, this phenomenon reduces the service life of components, increases maintenance costs, and risks causing downtime in the production process[3]. This phenomenon of corrosion and wear not only occurs naturally but is also accelerated by environmental and operational conditions such as the flow rate of the fluid and the content of active ions in the solution (including H^+ ions in H_2SO_4), as well as the mechanical load subjected to the components. Surface coating, or coating, is commonly used to slow down the corrosion process. The coating technique is a relatively economical approach to improving the durability of metal surfaces against chemical and physical degradation [4]. In recent years, epoxy resin has become a widely used coating base material because it has superior properties, such as high mechanical strength, strong adhesion, resistance to erosion and chemicals, and good thermal stability. However, to improve performance for extreme working conditions, aluminum (Al), silica carbide (SiC), and titanium dioxide (TiO_2) [5], for example, are added to epoxy resin to reinforce it. These particles increase hardness and wear resistance and create a barrier to the penetration of corrosive substances into the surface of the metal substrate [6].

Various studies have proven that adding ceramic and metal particles to an epoxy matrix can improve metal substrates' mechanical characteristics and corrosion protection. For example, a study by [7] showed that PVK/TiO_2 nanocomposites can significantly lower the corrosion rate of stainless steel in marine environments. Meanwhile, [8] showed that using sputtering techniques, PTFE/TiN coating on SS304 successfully transformed the surface to be almost super-hydrophobic and highly resistant to corrosive attack in chloride solutions. However, there are still gaps in the research regarding the specific effect of the combination of epoxy resin with Al–SiC and TiO_2–SiC on SS304 steel in the H_2SO_4 environment, a medium that represents corrosive conditions in palm oil mills [9]. Against this background, this study evaluated the effect of an epoxy resin coating layer mixed with aluminum, silica carbide, and titanium dioxide on the corrosion rate and wear of SS304 steel in sulfuric acid (H_2SO_4) solution media. This study also compares the performance of two types of coating composites, namely epoxy–Al–SiC and epoxy–TiO_2–SiC, to find the best composition for material protection against corrosion and wear [10]. Researchers used the weight loss method based on the ASTM G31 standard to analyze the corrosion rate and the Ogishi method to test the wear. This study should provide valuable scientific information for developing surface protection technologies for industrial applications, especially in high-acid and heavy-wear environments. In addition, the research results can also contribute to selecting optimal coating materials to extend the life of equipment, reduce maintenance costs, and improve the efficiency of production systems in the palm oil industry.

2. Material and Method

This research is a laboratory experimental study with a quantitative approach. The purpose of this experiment was to determine the effect of variations in the composition of epoxy resin coatings combined with aluminum (Al), silicon carbide (SiC), and titanium dioxide (TiO_2) on the corrosion rate and wear resistance of SS304 type stainless steel in sulfuric acid (H_2SO_4) media. The study was conducted using a comparative experimental method, in which two treatment groups (epoxy–Al–SiC and epoxy–TiO_2–SiC) were compared against uncoated conditions as controls.Specimen preparation. The specimen used in this study is SS304 stainless steel, cut with 50 x 25 x 6 mm dimensions. The specimen's surface is then cleansed using alcohol and coarse sandpaper to eliminate grease, corrosion, and debris for the best possible coating layer adherence.

Figure 1. Sanding process

Table 1. Fertilizer Content SS304

Steel	**C** *max*	**The** *Max*	**Mn** *max*	**P** *Max*	**S** *Max*	**CR**	**Ni**
304	0,08	1,00	2,00	0,045	0,03	18,0-20,0	8,0-10,5

Table 2. Mechanical Properties of SS304 Steel

Properties	**Value**
Tensile strength (MPa)	646
Yield strength (MPa)	270
Elongation (%)	50
Hardness rockwell B	82

2.1 Coating

The coating process on SS304 steel specimens begins with the preparation of the primary material, epoxy resin, which serves as the polymer matrix. The epoxy resin is mixed with a hardener at a 2:1 weight ratio—two parts epoxy to one part hardener. This ratio ensures optimal polymerization, resulting in a strong, dense, and highly adhesive coating on the metal substrate [12]. The initial step involves mixing the epoxy resin and hardener. Subsequently, a filler is added, consisting of microparticles such as aluminum powder, silicon carbide (SiC), and titanium dioxide (TiO_2). These materials enhance the mechanical properties and improve the coating's resistance to corrosion and wear. The particle mixture is incorporated into the epoxy solution across four treatment groups:

1. Raw material
2. Epoxy resin only
3. Group A: 50:25:25 ratio (epoxy + aluminum + silicon carbide)
4. Group B: 50:25:25 ratio (epoxy + titanium dioxide + silicon carbide)

Using a mechanical mixer, the entire mixture is stirred at a constant speed until a homogeneous blend is achieved, characterized by the absence of particle agglomeration and a uniform color. Once the mixture is prepared, the coating is manually applied to the surface of the SS304 specimens. Prior to application, the metal surfaces are cleaned using fine sandpaper and technical alcohol to remove oil, dust, and oxides that could hinder adhesion. The coating is applied using a brush with a one-way sweep technique to ensure even thickness across the surface [13].

The coating is applied gradually and with precision to meet the standard thickness requirements. The coating layer on each specimen is maintained within a range of 700 μm to 1000 μm, monitored using a digital paint thickness gauge to ensure uniformity across specimens [14]. This thickness was selected to provide optimal protection against corrosion and abrasion without altering the original geometric dimensions or shape of the specimen. After the coating process is complete, the specimens are left at room temperature for 24 hours to allow thorough curing (drying and hardening).


(a) (b) (c) (d)

Figure 2. (a) Raw; (b) Epoxy resin; (c) Epoxy, aluminum and silica carbide mixtures; (d) Mixture of epoxy, titanium dioxide and silica carbide

2.2 Preparation of H_2SO_4 solution

The solution used in this study is sulfuric acid (H_2SO_4), prepared for corrosion rate testing based on the ASTM G31-72 standard, which requires a minimum solution volume of 20 mL per cm² of submerged specimen surface area [15]. For laboratory-scale immersion testing, the minimum solution volume is calculated as follows:

Beam surface area formula:

$$\mathbf{A = 2(pl + pt + lt)}$$

$$\mathbf{A = 2(5 \times 2,5 + 5 \times 0,6 + 2,5 \times 0,6)}$$

$$\mathbf{A = 34\ cm^2}$$

The Ø3 mm hole is used solely for hanging and is not considered part of the exposed surface area; thus, the effective area remains 34 cm².

Required volume of H_2SO_4 solution:

Minimum solution volume = $\mathbf{20mL/cm^2 \times 34\ cm^2 = 680\ mL}$

To ensure safety and prevent saturation of the solution by corrosion products, the volume was rounded up:

Volume of H_2SO_4 solution per specimen: $\mathbf{700\ mL}$

Therefore, the minimum solution volume for a specimen with a surface area of 34 cm² is 700 mL. In this study, 700 mL of H_2SO_4 solution was used per container. Since eight containers were utilized, a total of 5600 mL of H_2SO_4 solution was prepared.

2.3 Corrosion rate test

The corrosion test was conducted using the weight loss method in accordance with ASTM G31-72 [15]. The objective was to determine the corrosion rate of SS304 steel specimens coated with an epoxy matrix containing silicon carbide, aluminum, and titanium dioxide, immersed in an H_2SO_4 solution.

The procedure involved weighing the initial mass of each SS304 specimen, immersing it in H_2SO_4 for 10 days, then cleaning and re-weighing the specimen to obtain the final mass. The corrosion rate was calculated based on the mass loss using the equation 1.

$$Cr = \frac{K \times (W_0 - W_1)}{A \times T \times D} \quad (1)$$

Information:

CR = Corrosion rate

K = Constant (3.45×10^7 for mm/year)

W_0 - W_1 = Weight difference (grams)

A = Specimen surface area (cm^2)

T = Soaking time (hours)

D = Material density (g/cm^3)

The dimensions of the corrosion rate test specimen, in accordance with ASTM G31-72, are illustrated in Fig. 3.

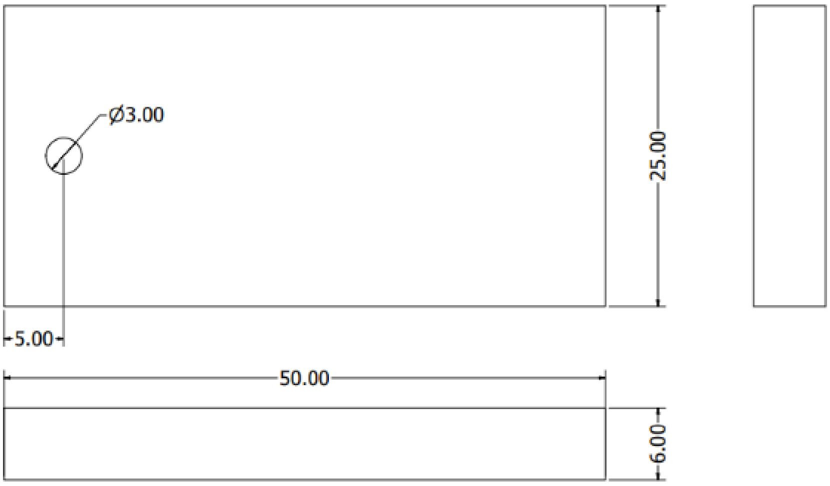
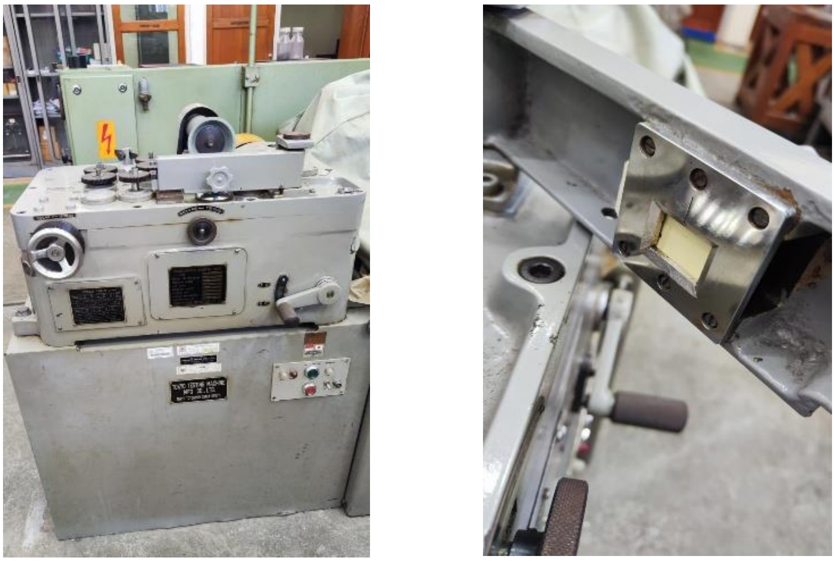


Figure 3. Corrosion Rate Test Dimensions

Figure 4. Corrosion rate test immersion process

2.4 Wear Test

The test was conducted using a universal testing machine (Tokyo Testing Machine MFG Co., Ltd.), in accordance with the ASTM G99 standard.



(a) (b)

Figure 5. (a) the wear of the testing machine; (b) Wear testing process

The wear test in this study was conducted to evaluate the surface resistance of SS304 steel specimens after treatment with epoxy coatings containing various reinforcing material mixtures. The test method employed was the Ogozi method, which assesses wear based on the frictional interaction between the specimen surface and an abrasive medium under controlled load and time conditions.

The procedure involved placing the specimen on a wear testing device, applying a specific load in accordance with the relevant standard, and subjecting it to abrasion against a rough surface at a constant rotational speed. The test duration was adjusted to ensure that wear results could be accurately compared across specimens. Upon completion of the test, the volume of material lost was measured and recorded as an indicator of wear severity. These results were used to compare the effectiveness of each coating type in enhancing wear resistance, with the specimen exhibiting the lowest volume loss considered to have superior wear performance [16].

$$W = \frac{B.b^3}{12r};\ V = \frac{W}{x} \tag{2}$$

Information:

W = Volume of the abrasive sample (mm^3)
B = swivel ring thickness (3.4 mm)
b = width of abrasive gap (mm)
r = rotary ring radius (15 mm)
V = wear rate (mm^3/mm)
x = glide distance (100,000 mm)

Wear tests were performed using the Ogoshi method (pin-on-disk configuration) in accordance with ASTM G99. The operating parameters were as follows: a normal load of 10 N, a rotational speed of 200 rpm, a sliding radius of 15 mm, and a test duration of 60 min. All tests were conducted under dry conditions at room temperature (25 ± 2 °C). Each condition was evaluated using two specimens (n = 2), and the results were reported as mean values. Mass loss was measured using an analytical balance with a resolution of ±0.1 mg, and the wear rate was calculated and expressed in $mm^3/(kg \cdot m)$. The dimensions of the wear test specimens, as specified by ASTM G99, are illustrated in Fig. 6.

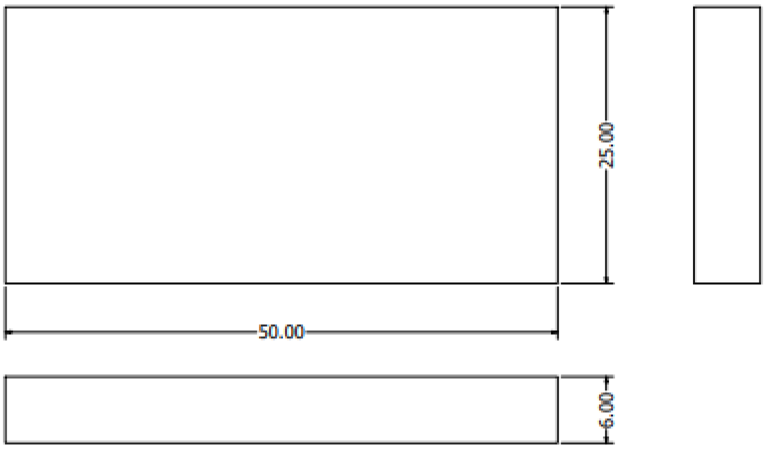


Figure 6. Wear Test Dimensions

3. Results and Discussion

A total of two specimens were used for each variation in both the corrosion and wear tests. Additionally, one spare specimen was prepared for each variation to account for any significant discrepancies in test results. All test data were averaged and presented graphically to facilitate comparison.

3.1 Corrosion Rate Test Results

The corrosion rate test was performed on SS304 steel specimens coated with epoxy resin and various composite mixtures. The results include the measured corrosion rate (CR) and the remaining coating thickness after exposure.

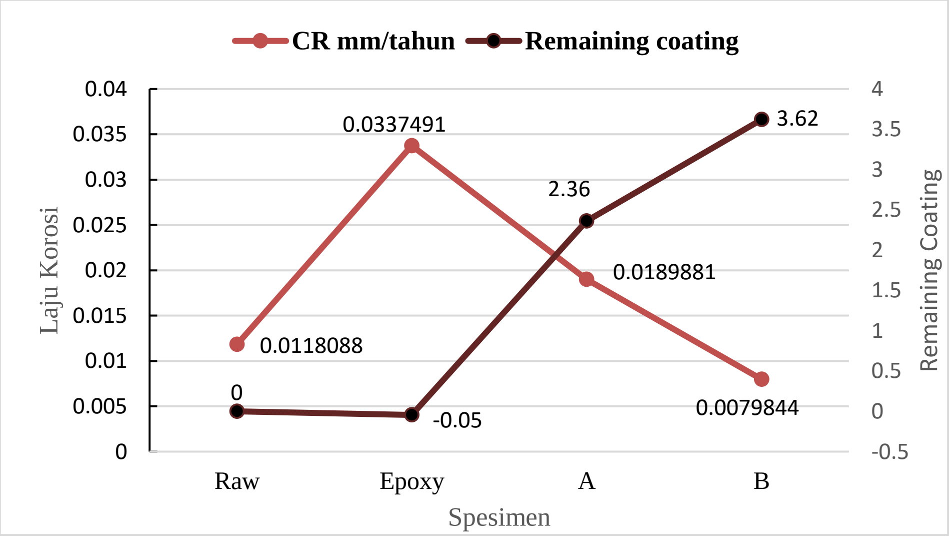
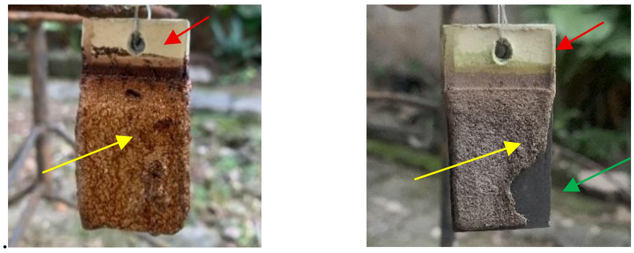


Figure7. Corrosion rate test comparison chart

Based on the average values presented in Fig. 7, the corrosion test results demonstrate the relationship between corrosion rate (CR, in mm/year) and remaining coating thickness across four specimen types: Raw, Epoxy, A, and B. Specimen B exhibited the best performance, with the lowest corrosion rate of 0.0079844 mm/year and the highest remaining coating thickness of 3.62 mm. This indicates that the protective coating applied to B was highly effective in resisting corrosion while maintaining its structural integrity during testing, thereby offering maximum protection to the base material. Raw specimens ranked second, with a corrosion rate of 0.0118088 mm/year. Specimen A placed third, with a corrosion rate of 0.0189881 mm/year and a remaining coating thickness of 2.36 mm. Although a substantial portion of the protective layer remained, its corrosion resistance was inferior to that of Specimens B. Epoxy specimens showed the poorest performance, with the highest corrosion rate of 0.0337491 mm/year and a negative remaining coating value of −0.05 mm, indicating complete degradation or loss of the protective layer. These results suggest that unmodified epoxy coatings are ineffective in resisting corrosion under the specified test conditions. An image of the wear test results is provided in Fig. 8.



(a) (b)

Figure 8. (a) Specimen after immersion (b) Specimen after cleaning and drying

Fig. 8 illustrates the condition of the specimen after corrosion testing, showing severe degradation as indicated by the yellow arrow. The metal surface exhibits significant erosion, particularly on the underside of the specimen—an area subjected to prolonged and intense immersion in the corrosive solution. The remaining coating is visible only in the regions marked by the yellow and red arrows. These areas retain a thin protective layer, and the boundary between the coated and corroded zones is distinctly visible. This observation suggests that the protective layer was largely effective in shielding the SS304 steel surface. Most of the corrosion occurred within the coating itself, with only a small portion of the steel substrate affected, as indicated by the green arrow. The test results revealed that the corrosion rates of Specimens A and B were significantly lower than those of specimens coated with epoxy. This indicates that the incorporation of additives such as silicon carbide (SiC), titanium dioxide (TiO_2), and aluminum powder into the epoxy matrix plays a critical role in reducing corrosion rates on metal surfaces [17]. Silicon carbide contributes high hardness and wear resistance, thereby mechanically reinforcing the protective layer. Titanium dioxide functions as an inert pigment and enhances chemical resistance against corrosive environments. Aluminum powder serves as a filler and physical barrier, impeding the diffusion of corrosive ions toward the metal surface [18]. The superior corrosion resistance of specimen B (epoxy–TiO_2–SiC) is primarily attributed to the barrier effect of TiO_2 particles. As a chemically stable ceramic oxide with high electrical resistivity, TiO_2 reduces the permeability of the epoxy matrix to corrosive species (H^+ and SO_4^{2-} ions) by occupying microvoids and inducing a more tortuous diffusion pathway. Furthermore, the incorporation of SiC particles enhances the mechanical integrity of the coating, thereby minimizing microcrack formation that could act as corrosion pathways. These findings align with previous studies that have reported improved barrier performance in epoxy coatings due to the presence of TiO_2[7]. The synergistic combination of these three materials within the epoxy matrix produces a compact, homogeneous protective layer that effectively resists the penetration of corrosive agents. These findings confirm that the strategic selection and integration of coating materials significantly enhance corrosion resistance and improve the long-term performance of the protective system.

3.2 Wear test results

In this study, wear testing was conducted on SS304 material both before and after the application of composite coatings. The tests were performed using the Ogoshi method, in accordance with the ASTM G99 standard.

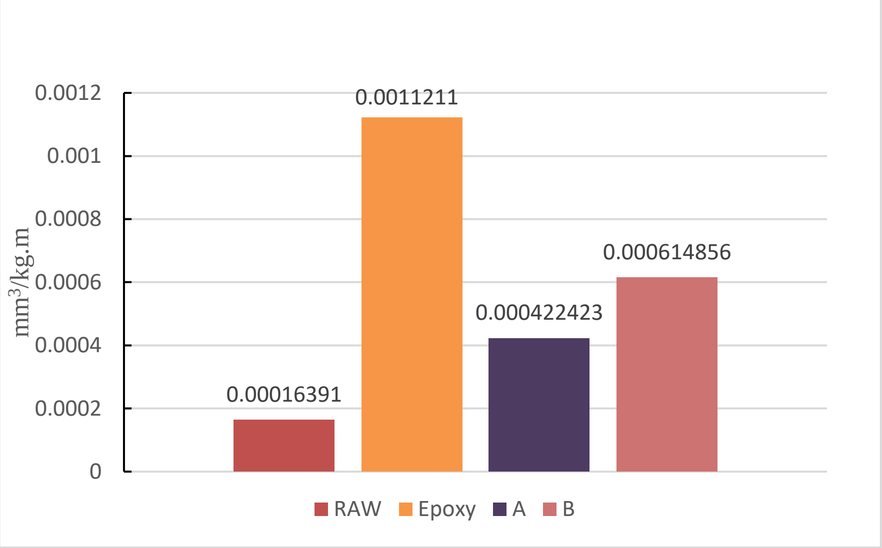


Figure 9. Comparison graph of wear tests

Fig. 9 presents the average wear values for each specimen, comparing coated and uncoated SS304 steel samples. Based on the test results, the RAW specimen exhibited the lowest wear value among all specimens, measured at 0.00016391 $mm^3/kg\cdot m$. This result is attributed to the absence of a coating, which allowed direct contact between the abrasive surface and the metal. Since stainless steel possesses greater hardness than the applied coating materials, it demonstrated superior resistance to wear under the test conditions.

In contrast, the Epoxy specimen showed the highest wear value of 0.0011211 $mm^3/kg\cdot m$, indicating the lowest resistance to wear among all specimens. Specimen A demonstrated a wear value of 0.000422423 $mm^3/kg\cdot m$, representing a 62.4% reduction in wear compared to the Epoxy specimen. Specimen B recorded a wear value of 0.000614856 $mm^3/kg\cdot m$, which is higher than Specimen A but lower than the Epoxy specimen. This suggests that Specimen B offers moderate wear resistance—better than pure epoxy, but inferior to Specimen A.

Overall, Specimen A exhibited the best wear resistance among the coated specimens. The visual condition of the specimens after wear testing is shown in Fig. 9.

Fig. 10 presents the visual results of the wear test. Notably, the area indicated by the black arrow shows surface damage in the form of peeling. The red arrow highlights the presence of streaks, which are indicative of erosion or abrasion caused by frictional forces. This wear phenomenon is attributed to oscillating loading pressure and high rotational speed during testing. Such damage may also result from materials that lack sufficient resistance to high-speed contact, leading to surface scratching and peeling.The presence of streaks and peeling confirms that the specimen experienced significant structural degradation under extreme operational conditions.

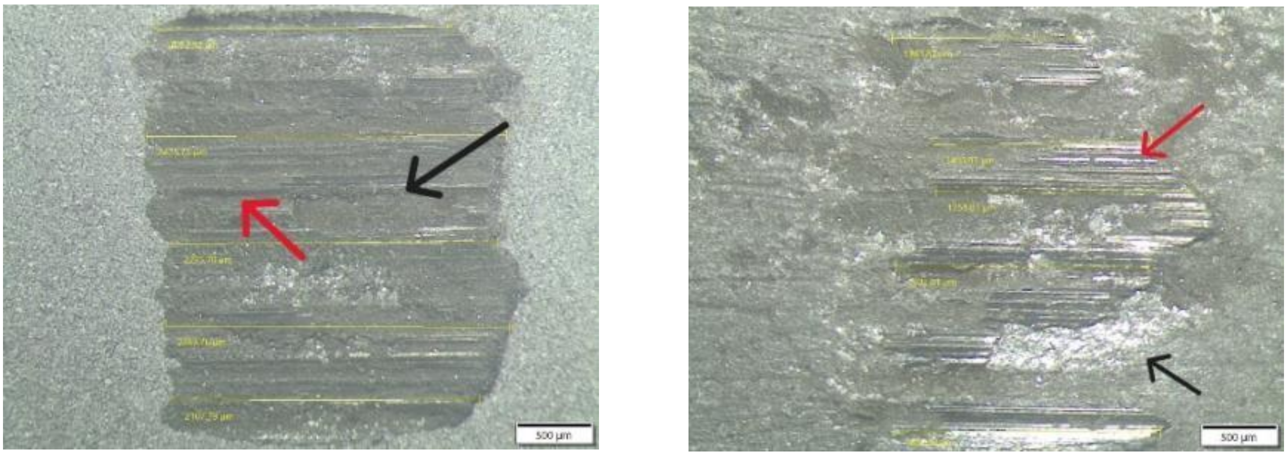


Figure 10. Micro photo of wear testing

Wear levels in Specimens A and B were higher than those observed in the Epoxy specimen. However, the test results for Specimens A and B demonstrate that the inclusion of silicon carbide (SiC), titanium dioxide (TiO_2), and aluminum powder in the coating composition significantly influences the wear rate. These findings underscore the importance of material composition in enhancing wear resistance.It has been established that the addition of SiC to the composite mixture increases surface hardness and reduces wear [19]. The superior wear resistance of specimen A (epoxy–Al–SiC) results from the synergistic contributions of SiC and Al particles. SiC, owing to its high hardness, offers excellent abrasion resistance, while Al enhances toughness and energy absorption, thereby mitigating crack initiation and propagation under mechanical loading. This balance between hardness and toughness accounts for the improved wear performance of composite A compared to pure epoxy or coatings lacking metallic fillers [6].This improvement is attributed to the high hardness of SiC, which reinforces the epoxy matrix and minimizes material loss. Furthermore, SiC particles help inhibit crack formation on the composite surface, thereby reducing abrasive wear [20].

4. Conclusion

The results indicate that surface coating of SS304 steel with modified epoxy resin containing titanium dioxide (TiO_2) and silicon carbide (SiC) particles (Specimen B) provides the most effective corrosion protection, as evidenced by the lowest corrosion rate and substantial remaining coating thickness after testing.

Specimen A, composed of epoxy resin reinforced with aluminum and SiC particles, demonstrated superior wear resistance compared to epoxy coated specimens. In contrast, specimens coated with pure epoxy resin—without reinforcing particles—exhibited the poorest performance in both corrosion and wear resistance. The incorporation of SiC, TiO_2, and aluminum powder significantly enhanced the mechanical strength and chemical durability of the coating. These findings underscore the importance of selecting an appropriate coating composition to extend service life and improve system efficiency in environments subject to corrosive and abrasive conditions.

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