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Erosion wear performance of cobalt alloy coating prepared through electrodeposition method

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KEYWORDS

CoNiFe
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Wear erosion
Surface roughness
Hardness

ABSTRACT

Coating is commonly used to improve mechanical and physical properties. Electrodeposition is a method used for applying a protective coating. It is frequently used in industry due to its ability to produce high-quality coatings. However, there is limited research comparing how variations in deposition time, pH, and current collectively affect the mechanical and surface properties of CoNiFe nanoparticles coating on mild steel. The purpose of the research was to determine the hardness, surface roughness and wear erosion resistance of Cobalt-Nickel-Iron (CoNiFe) nanoparticles coating on a mild steel substrate subject to the influences of deposition time, pH and current. In this study, three different deposition times were used: 15, 30, and 45 minutes. The electroplating solution's operating temperature was 50 ± 5 ^{0}C, the current supplied was 1.5, 2.0, and 3.0 A together with electroplating bath pH setting of 3.0 and 5.0. The coating hardness trend increased as deposition time increased, with the highest hardness reported at 45 minutes coating being 320.680 HV. The CoNiFe nanoparticles coating with a 30-minute coating at pH 3, I: 1.5A had the lowest surface roughness measured at 2.667 µm, while uncoated mild steel had the highest surface roughness measured at 4.233 µm. Erosive wear performance of CoNiFe nanoparticles coating at 5 minutes and pH 3, I: 1.5A was the lowest with a recorded wear loss percentage of 26.44 %. The highest percentage of wear loss of 59.59% was recorded by CoNiFe nanoparticles coating at 30 minutes with pH 5, I: 1.5A. From these findings, it is possible to conclude that deposition of CoNiFe alloy coating could enhance the performance of mild steel substrate for vast engineering applications.

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1.0 INTRODUCTION

Protecting machinery from potential harm has arisen as a critical concern across a variety of sectors. Many researchers emphasize the critical need to protect machinery and equipment from erosive wear processes, which significantly impact the durability and functionality of industrial component (Del Giudice et al. 2024). Solid particle erosion, where discrete solid particles strike a surface and slurry erosion, characterized by the impact of solid particles suspended in a fluid which are two prominent forms of wear that threaten the integrity of machinery. Machinery such as crushers, grinders, and conveyors are some of the perfect examples of machinery exposed to extremely abrasive and erosive conditions in the mining industry. Electroplating is one of the most used coating processes because of its ability to provide strength, hardness, and resistance to corrosion and wear (Zabri et al. 2022). The mechanical properties of electroplated materials can be changed by adjusting the electrolyte composition and coating parameters. By submerging the substrate in a electrolyte's solution, the electroplating process produces a coating with robust substrate adhesion and mechanical qualities that may be adjusted to suit specific application. However, composition and deposition technique can affect how well cobalt alloy coatings work.

Hard chromium coatings have received a lot of interest due to their excellent tribological and corrosion performance. However, there is a worldwide need to replace such coatings in industrial applications due to technological issues, environmental concerns, and legislation. Cobalt alloy electrodeposits are a viable alternative to hard chromium deposits from acidic Cr (VI) baths in a variety of engineering applications due to their superior corrosion resistance and microhardness (Safavi et al. 2021). Cobalt alloys are gaining popularity as materials for use in a variety of sectors due to their great resistance to corrosion, abrasives, and erosive wear in harsh environments, as well as their ability to work at high temperatures (Klarstrom et al. 2017). Cobalt alloy coating dramatically reduces damage to these parts, resulting in lower maintenance expenses and increased operational effectiveness (Habib et al. 2021). Pipelines, valves, and drilling equipment are among the parts used in the oil and gas industry that are subjected to slurry flows and corrosive fluids (Ige et al. 2020). Cobalt-based coatings ensure the dependability and longevity of crucial equipment by offering the toughness needed to survive these harsh conditions (Kim et al. 2021). In the aerospace sector, cobalt alloy coatings are quite helpful, especially for turbine engines and other high-temperature parts. The ability of cobalt alloys to maintain their integrity at high temperatures guarantees the safe and effective operation of aircraft engines, enhancing overall flight performance and safety (Fan, 2025). The creation and use of sophisticated coatings have become well-known as practical methods to lessen erosive wear in order to address these issues. By limiting direct exposure to erosive forces, coatings act as protective barriers, improving machinery performance and longevity.

Thus, it's critical to comprehend how various elements affect these coatings' ability to withstand erosion. Previous researchers have investigated several criteria that influence the performance of cobalt alloy coatings. Previous studies on CoNiFe nanoparticle coatings have investigated how variations in deposition time and slurry erosion testing speed affect the coating properties (Hyie et al. 2016; Hyie et al. 2019). However, further research is needed to understand how the effect of deposition parameters such as electrolyte pH and current and deposition time affects the properties of coatings. The purpose of this work is to examine how coatings made of cobalt alloy with change in parameters such as current, electrolyte pH and deposition times react to constant erosive conditions. By expanding on earlier research findings, this study seeks to enhance the performance of cobalt alloy coatings in erosive conditions.

2.0 EXPERIMENTAL PROCEDURE

2.1 Sample Preparation

Mild steel (AISI 1018 Steel) was chosen as substrates for this study. Mild steel plate with thickness of 2 mm was cut into dimensions of 70 mm x 20 mm x 2 mm for each sample. 2 sets of samples were prepared where each set contained six (6) samples. A hole was made at the center of the mild steel substrate to secure the insertion of samples onto the rotational steel rod before secured inside slurry erosion pot for slurry erosion wear test. Figure 1 shows the illustration of the dimension of the prepared mild steel substrates. The substrate was cleaned through surface grinding method to remove the oxide layers using a 120-grit flap disk. It was then polished using 240 and 320 grit sandpaper flap disks, followed by mirror polished using a cloth polishing wheel machine to get mirror like surfaces before proceeding with coating process.

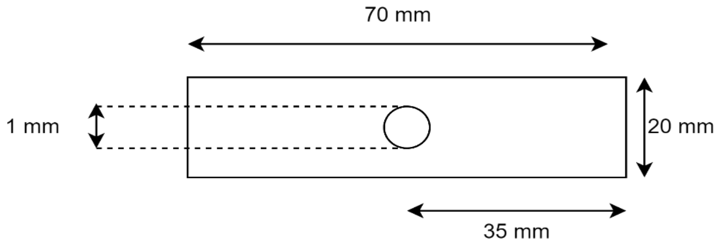

Figure 1: Dimension of mild steel substrates.

2.2 Coating Preparation

CoNiFe nanoparticles coating were prepared using the electrodeposition method with a combination of sulphate-based materials such as nickel sulphate, iron (II) sulphate and cobalt sulphate. The addition of materials such as ascorbic acid, boric acid, and saccharine which also serve as pH buffer, grain refinement agent and internal stress reliever were used for preparation of the electrolyte bath. Both mild steel substrate and platinum mesh plate were positioned at cathode and anode, respectively. The powder mixture applied were scale up accordingly with 1 Litre electrolyte based on optimization from previous studies (Zabri et al. 2023) (Zabri et al. 2025). Current setting, deposition times, and electrolyte pH were among the parameters measured during the electrodeposition process. Table 1 shows the material used for preparing CoNiFe nanoparticles electrodeposition coating.

Table 1: The materials used for preparing the CoNiFe nanoparticles electrodepositon coating.

Material	**No. of Moles**
Nickel sulphate (NiSO4)	0.050
Iron (II) sulphate (FeSO4)	0.133
Cobalt sulphate (CoSO4)	0.020
Boric acid (H3 BO3)	0.267
Ascorbic acid (C6 H8 O6)	0.067
Saccharine (C7 H5 NO3 S)	0.007

The mixture for the sulphate bath was heated and maintained at a constant temperature ranging 50 ± 5 ^{0}C. The pH of the bath's composition varied between 3.0 and 5.0 while current setting varied between 1.5 A, 2.0A and 3.0 A, respectively. The CoNiFe nanoparticles coating were set coated for 15, 30, and 45 minutes to check the effect of coating at different deposition time. In order to determine the coating mass for each sample, the sample were weighed both before and after coating using a digital weighing scale. Table 2 shows each of the sample settings for the study.

Table 2: Electrodeposition setting used for the coating process.

Sample Number (Set 1 and 2)	Deposition time (min)	Current (A)	pH
1	15	1.5	3
2	30	1.5	3
3	45	1.5	3
4	30	2.0	3
5	30	3.0	3
6	30	1.5	5

2.3 Vickers Hardness Test

The hardness of CoNiFe nanoparticles coating samples was determined using a Vickers hardness tester, with an average of five (5) measurements per sample. Seven (7) samples were measured, including a raw mild steel substrate as a reference substrate for comparison to the CoNiFe nanoparticles coating. To evaluate the hardness of the CoNiFe nanoparticles coating, two (2) separate variables were established, including a comparison of the influence of time deposition, and differences in current and electrolyte pH setting which are explained further in the next section.

2.4 Surface Roughness Test

The surface roughness of CoNiFe nanoparticles coating samples was assessed using a Mitutoyo surface profiler, with an average of 5 measurements per substrate. 7 substrates were measured including raw mild steel substrate as reference substrate for comparison with CoNiFe nanoparticles coating. To assess the roughness of the CoNiFe nanoparticles coating, three (3) different parameters were set up such as comparison on influence of time deposition, difference in current setting and electrolyte pH value which is explained furthermore in the following section.

2.5 Slurry Erosion Test

The erosive wear test was conducted using a slurry erosion tester machine (Model TR-40, Ducom) inconformity with ASTM G40 Standard. This is done by immersing the mild steel substrate in slurry of the desired sand to water ratio and rotating the samples (rectangular shape) with fixed duration and speed. As a result, erosion of the coating on mild steel substrates and weight loss of CoNiFe coating can be determined. The sample dimension used were 70 mm x 20 mm x 2 mm. Constant rotation speed of 500 rpm were applied and individually operated for 14 h. The erosion wear rate measured from percentile of mass loss was recorded for every 2 hours. Beach sands having an average particle size of 200-300 μm were used in the slurry erosion test. About 60 wt% -40 wt% of sand to water ratio have been prepared for the test. Table 3 shows the parameters for slurry erosion testing. This type of wear test was chosen to assess the CoNiFe nanoparticles under erosion environment. Figure 2 shows the illustration of slurry erosion wear machine (TR-401, Ducom) used for erosion study.

Table 3: Parameters for slurry erosion testing.

Parameters	**Setting details**
Slurry mixture	70% beach sand size 200-300 μm + Distilled water
Rotation speed	500 rpm (fixed speed)
Rotation time	14 hours with intervals every 2 hours
Temperature	Room condition

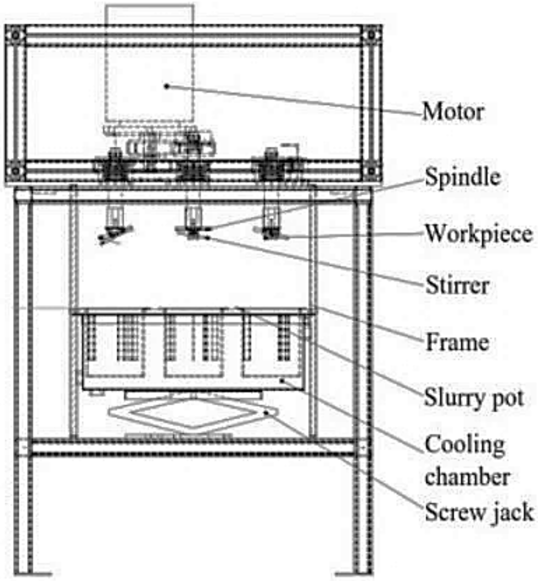

Figure 2: Slurry erosion wear machine used to conduct erosion study.

3.0 RESULTS AND DISCUSSION

3.1 Vickers Hardness

3.1.1 Influence of deposition times on CoNiFe nanoparticles coating hardness

The hardness results were compared based on coating deposition periods that were constant in current and pH. Figure 3 demonstrates that the average hardness of the samples increases with higher CoNiFe coating deposition times. The CoNiFe nanoparticles coating hardness for 45-min coating (320.68 HV) was greater than sample coated for 15-min coating (226.022 HV) and 30-min coating (258.102 HV), respectively. The coating produced at three distinct deposition times enhanced the hardness value when compared to uncoated mild steel susbtrate, which had the lowest value of 171.44 HV.

A longer deposition period allows for greater amount of CoNiFe nanoparticles coating to develop on the mild steel substrate, resulting in a steady increase in surface hardness. The increment is achievable due to changes in the phase structure, solid hardening mechanism, particle size of the nanoparticles deposit and effect of porosity (Hyie et al. 2016). Additionally, longer deposition times allow for the deposition of additional CoNiFe nanoparticles coating on the mild steel substrate, producing a thicker layer that hardens the coating's surface (Resali et al. 2013).

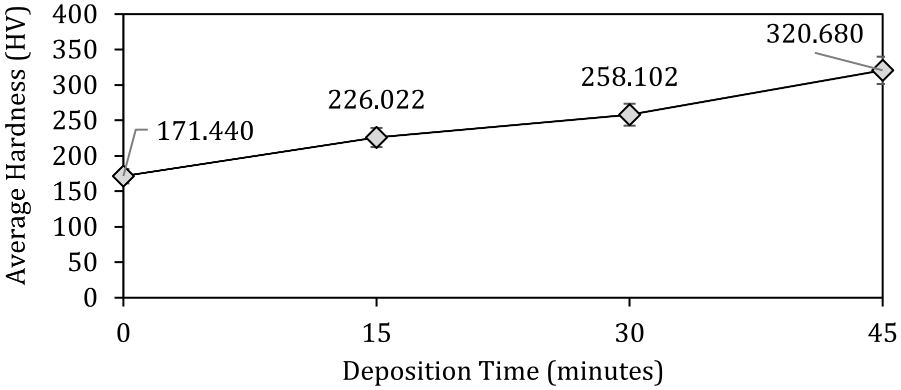

Figure 3: Microhardness (HV) versus deposition time.

3.1.2 Influence of different applied current and electrolyte pH on CoNiFe nanoparticles coating hardness

Figure 4 depicts a comparison of CoNiFe nanoparticles coating hardness with respect to applied current. The current setting applied during coating affects the hardness of the coating. It is worth noting that by maintaining the coating deposition duration and electrolyte pH constant (Current:1.5 A; pH:3), the hardness of the electrodeposited CoNiFe nanoparticles coating increases (from 171.440 HV to 320.680 HV) with the current applied during the coating process. A larger current supplied during the electrodeposition process induces a faster deposition rate and may promote the nucleation and growth of smaller grains, which accounts for the increasing pattern in average microhardness (Saraloğlu Güler et al. 2014). Higher dislocation density in smaller grains reduce dislocation motion and improve microhardness (Yoo et al. 2006). Increased microhardness values could be the consequence of better grain refinement at a current intensity of 3A as opposed to 1.5A.

Figure 5 depicts a comparison of CoNiFe nanoparticles coating hardness with respect to current and electrolyte pH setting. It is observed that the electrolyte pH of CoNiFe nanoparticles coating influences its overall bond strength and adherence to the substrate whereby the coating process utilizing a lower electrolyte pH value (pH:3) has a greater average hardness of 258.102 HV than the substrate coated with a higher electrolyte pH value (pH:5). The decrease in microhardness from 258.102 HV to 211.74 HV could be attributed to changes in coating structure and properties as the pH varies from 3 to 5. At lower pH, the rate of electrodeposition reaction kinetics is favorable and hydrogen evolution decrease, resulting in a smoother, uniform and compact layer of covering (Tientong et al. 2013; Liu et al. 2022). It is well accepted that a material's hardness is optimal when its particle size is smaller as dislocation density in smaller grains is higher and limits dislocation motion (Farooq et al. 2022; Khanlari 2015). Hence, the electrodeposition process may be less successful and produce larger particle sizes at pH 5, due to thinner layer of coating that leads to potential agglomeration and void formation in the microstructure (Resali et al. 2013). At pH 5, these structural changes could cause a decrease in microhardness. Introduction of CoNiFe nanoparticles coating in general also increase the hardness of mild steel.

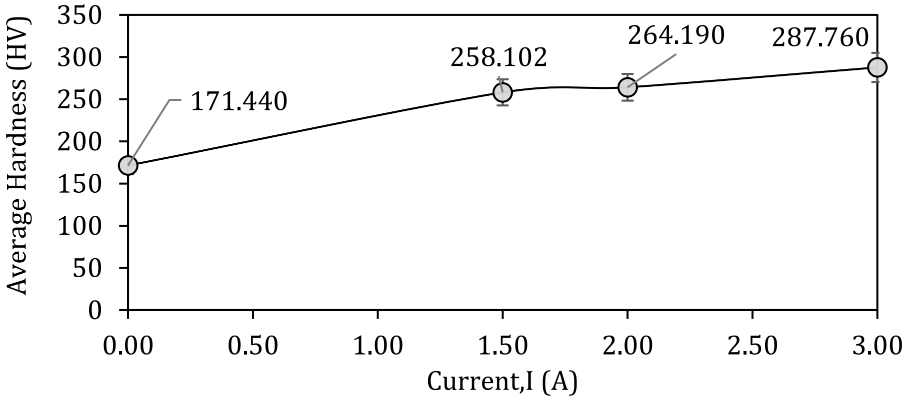

Figure 4: The CoNiFe nanoparticles coating hardness versus applied current.

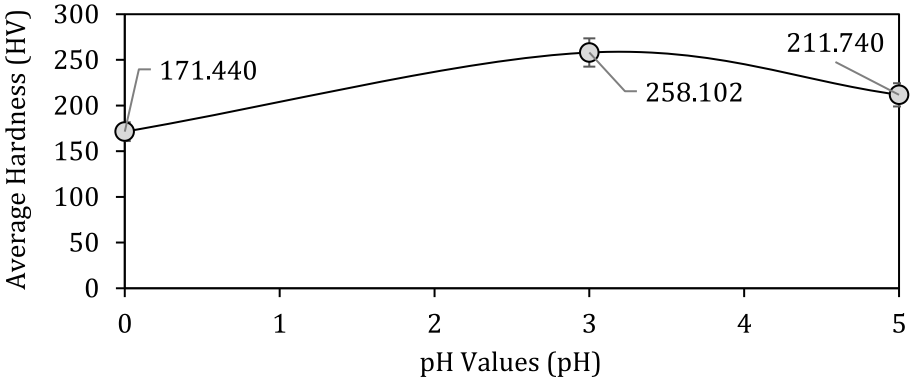

Figure 5: The CoNiFe nanoparticles coating hardness versus electrolyte pH value.

3.2 Surface Roughness

3.2.1 Influence of deposition time on CoNiFe nanoparticles coating surface roughness

The correlation between surface roughness with respect to CoNiFe nanoparticles coating deposition times is depicted in Figure 6. It was discovered that each sample had a different level of surface roughness. The sample that was coated for 30-min coating had the lowest surface roughness (2.667 μm), while the sample that was coated for 15-min coating had the highest surface roughness (3.734 μm). An increase in surface roughness was observed for the 45-minute coating (2.954 μm) relative to the 30-minute coating, indicating a rougher surface morphology associated with higher deposition time. The increase in nucleation density may have led to the formation of densely stacked particles, thereby causing a slight increase in surface roughness observed at the 45-minute coating (Hyie et al. 2016).

CoNiFe nanoparticles synthesized at earlier deposition time may have increased surface roughness due to the presence of voids caused by partial CoNiFe nanoparticles coating coverage of the substrate surfaces. Compared to others, longer deposition times (30-min coating) resulted in a more refined coating surface, as seen by a drop in surface roughness value (Siegel et al. 2012). Meanwhile, the 15-min coating substrate has higher surface roughness than others probably due to the existence of voids during the electrodeposition process (Hyie et al. 2016). Furthermore, the slight increase in surface roughness at 45-min coating could be attributed to the formation of clusters with stacking particle sizes and dense populations as nucleation density increases (Jiang et al. 2017).

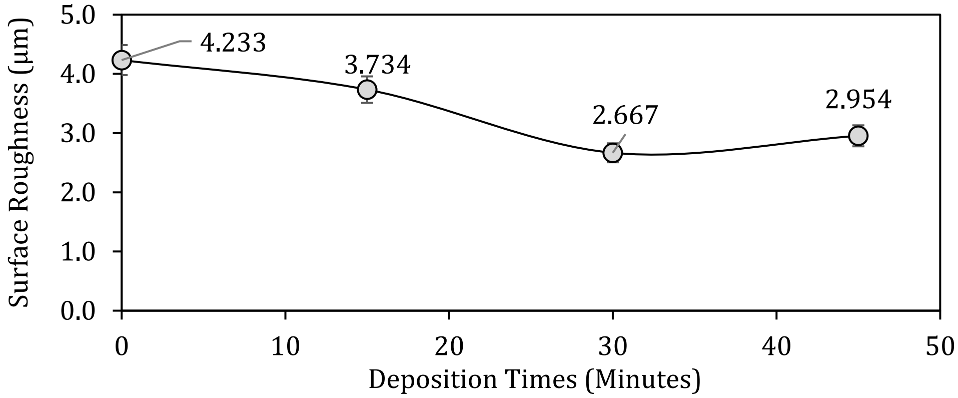

Figure 6: The CoNiFe nanoparticles coating surface roughness versus deposition time.

3.2.2 Influence of different applied current and electrolyte pH on CoNiFe nanoparticles coating surface roughness

Based on Figure 7, it is important to note that increasing applied current during electrodeposition process is capable of increasing the surface roughness of the coating. Surface roughness for 30-min coating at 1.5 A (2.667 µm) was lower than surface roughness of 30-min coating at 2.0 A (2.893 µm) and 30-min coating at 3.0 A (3.074 µm). One possible explanation for the increase in surface roughness could be due to a faster deposition rate brought about by a higher current delivered during the electrodeposition process (Ebrahimi et al. 2003). The higher deposition rate resulted in a thicker and more rough coating on the mild steel surface (Wang et al. 2021).

The pH level of a solution can affect the compactness of coatings and their resistance to wear. From Figure 8, It is noteworthy to mention that the results indicate a positive correlation between the pH value and the surface roughness value. When coated mild steel was subjected to a 30-min coating (pH: 5; I:1.5A), the surface roughness of the mild steel CoNiFe nanoparticles coating was higher than that of coated mild steel with lower pH value (pH: 3; I:1.5A). Similar pattern were observed by Julka et.al where the authors discovered the surface roughness value increases with increase in electrolyte pH value (Julka et al. 2016). As a result of a decreased deposition rate caused by a higher electrolyte pH value, less coating material was deposited onto the surface at the same current setting (Nan et al. 2023). Because of this, there may be a decrease in coating thickness and an ineffective filling or levelling out of surface roughness, which results in increased surface roughness.

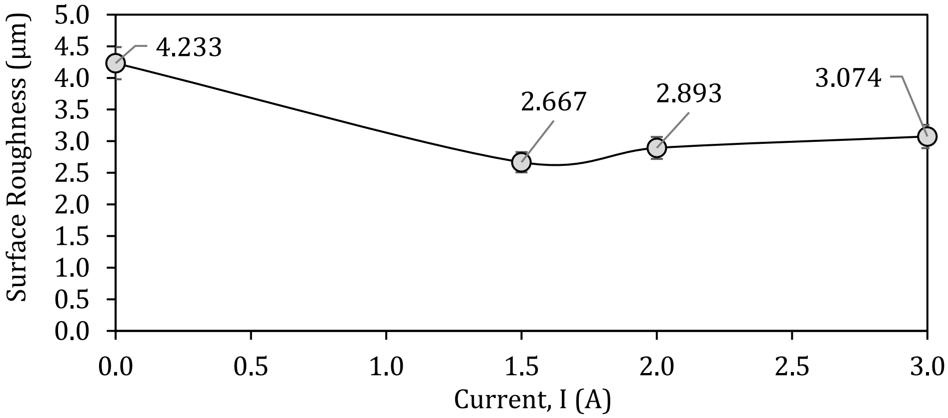

Figure 7: The CoNiFe nanoparticles coating surface roughness versus applied current.

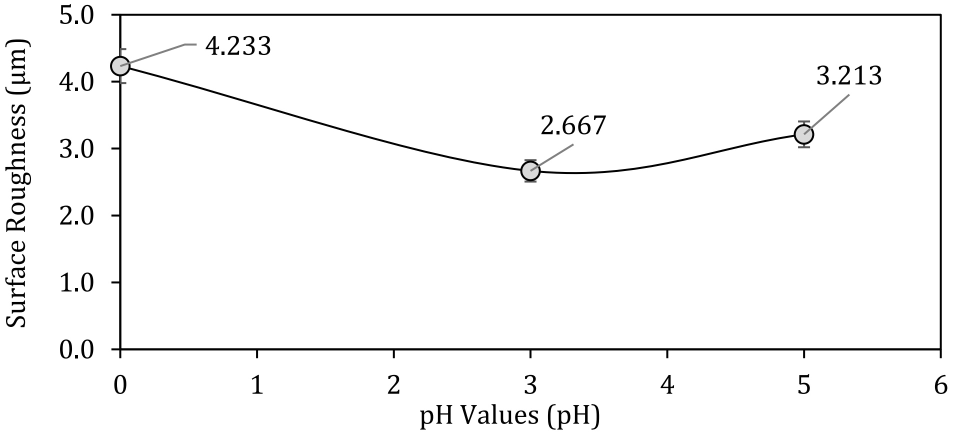

Figure 8: The CoNiFe nanoparticles coating surface roughness versus electrolyte pH value.

3.3 Mass of CoNiFe Nanoparticles Coating

Table 4 displays the variance in weight of the CoNiFe nanoparticles coating on mild steel substrate. It is worth noting that sample 3 (45 minutes deposition time, I:1.5A; pH 3) recorded the highest mass of CoNiFe nanoparticles coating (0.9348 g) due to implementation of highest deposition time. Sample 3 (45 minutes deposition time, I:1.5A; pH 3) is the highest compared to sample 2 (30 minutes deposition time, I:1.5A; pH 3) and sample 1 (15 minutes deposition time, I:1.5A; pH 3) which both recorded 0.5665g and 0.2871 g, respectively. Similar trend were obtained by M.Z Zabri et.al where the net coating's mass increases as more coatings deposited on the mild steel substrate due to a longer deposition period (Zabri et al. 2024).

Table 4: Mass of the CoNiFe nanoparticles coating on mild steel substrate.

Samples	Variables	Deposition time (min)	Mass (g), before coating	Mass (g), after coating	Mass of coating (g)
1	pH=3, I=1.5A	15	18.6679	18.955	0.2871
2	pH=3, I=1.5A	30	18.3275	18.894	0.5665
3	pH=3, I=1.5A	45	18.9422	19.877	0.9348
4	pH=3, I=2.0A	30	17.1422	17.8911	0.7489
5	pH=3, I=3.0A	30	17.7357	18.5928	0.8571
6	pH=5, I=1.5A	30	17.2742	17.7429	0.4687

For different applied currents aspect (constant 30 minutes deposition times and pH 3), sample 5 (I:3.0 A) recorded the highest mass of coating (0.8571 g) compared to samples 4 (I:2.0 A) and 2 (I:1.5 A) with both samples accounted a coating mass of 0.7489 g and 0.5665 g, respectively. As for comparison with respect to electrolyte pH (deposition time and current were constant), sample 2 (pH 3) has a higher mass of coating, 0.5665 g than sample 6 (pH 5), 0.4687 g. Figure 9 shows the differences in variables which attributes to the changing of CoNiFe nanoparticles coating mass.

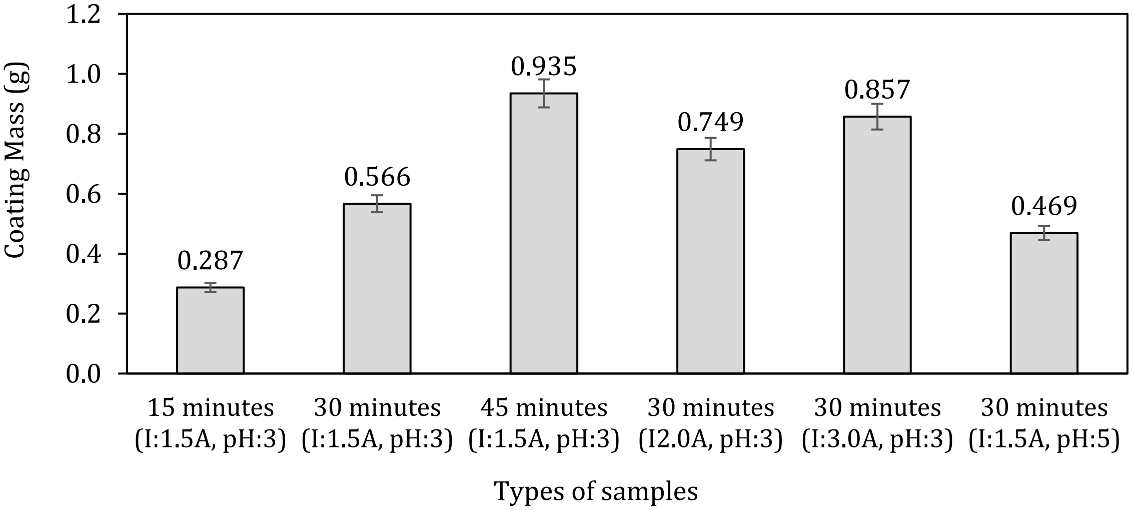

Figure 9: Differences in variables which are attributed to the changing of the CoNiFe nanoparticles coating mass.

3.4 Slurry Erosion

Table 5 and Figure 10 tabulate and illustrate the percentage of weight loss of the CoNiFe coating for 14 hours duration of slurry erosion test. Fine sand with particle size range of 200-300 μm was used in the slurry erosive wear tests, which were run at a constant 500-rpm rotating speed.

Table 5. Wear loss percentage of the CoNiFe nanoparticles samples.

Samples	Deposition time (min)	Variables	Maximum wear loss (g)	Mass of coating (g)	Wear loss percentage (%)
1	15	pH=3, I=1.5A	0.1578	0.2871	54.96
2	30	pH=3, I=1.5A	0.1801	0.5665	31.79
3	45	pH=3, I=1.5A	0.2472	0.9348	26.44
4	30	pH=3, I=2.0A	0.2239	0.7489	29.90
5	30	pH=3, I=3.0A	0.2397	0.8571	27.97
6	30	pH=5, I=1.5A	0.2793	0.4687	59.59

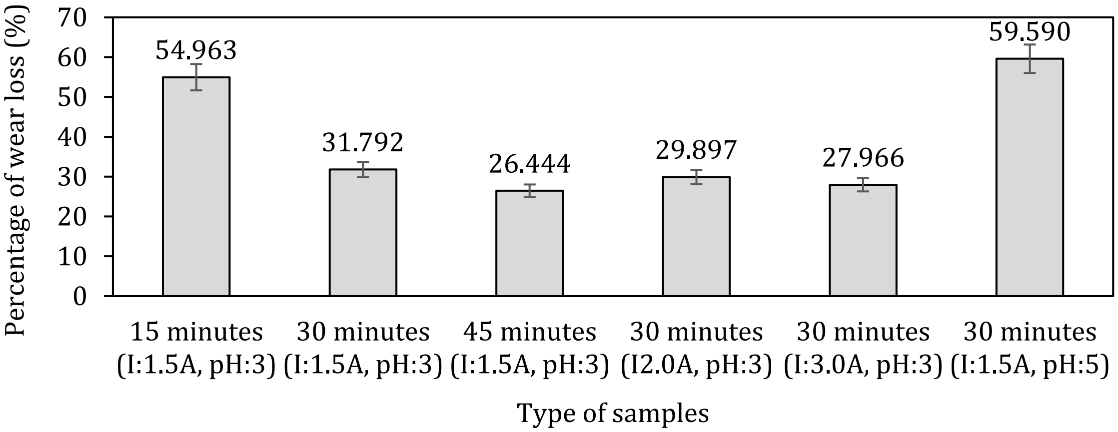

Figure 10: The CoNiFe nanoparticles wear loss percentages.

All coatings showed erosion wear, with roughly 26 – 60% of the coating removed over the fourteen (14) hour test. It has been discovered that CoNiFe nanoparticles coating material loss increases almost linearly with test duration. With extended testing times, it was discovered that more sand particles in the slurry mixture attacked and eroded the CoNiFe coating (Roseley et al. 2022). Due to the frequent impinging action of sediment particles, more material damage was caused to the surface of the susbtrates (Narváez et al. 2023).

In order to compare the erosion wear rate on coating substrate prepared at different deposition times, 15-min, 30 min and 45-min deposition duration were selected. It can be observed that coating prepared at 45-min deposition time seems to have the best erosion wear resistance as the sample produced the least mass loss. The 30-min coating has significantly shadowed the result of 45-min coating with minor difference after 11 hours of slurry erosion test. The least erosion wear resistance was recorded by 15-min coating. This may be associated with the existence of voids in 15-min coating that elevated the erosion process. The result was further supported by previous work (Hyie et al. 2016). The percentage of wear loss after fourteen (14) hours for 30-min coating (1.5A, pH 3) and 45-min coating (1.5A, pH 3) showed a significant improvement of wear performance by approximately 42.16 % and 51.89 % compared to 15-min coating (1.5A, pH 3). Figures 11 represent the CoNiFe nanoparticles wear loss percentages as deposition time increases.

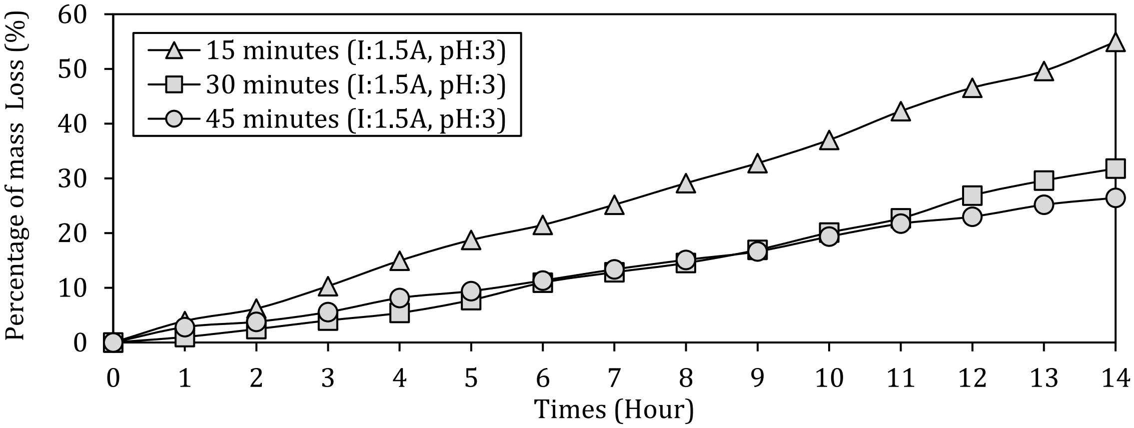

Figure 11: The CoNiFe nanoparticles wear loss percentages as deposition time increases.

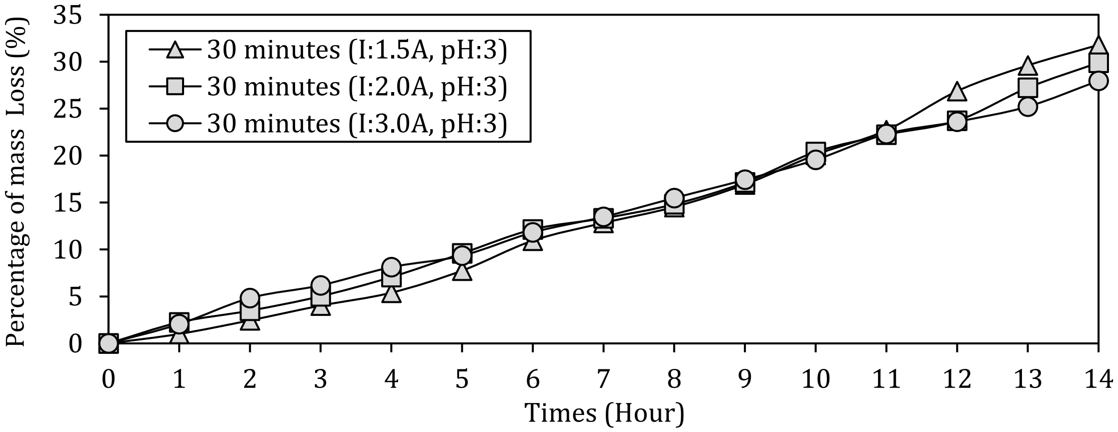

Figure 12: CoNiFe nanoparticles wear loss percentages as current intensity increases.

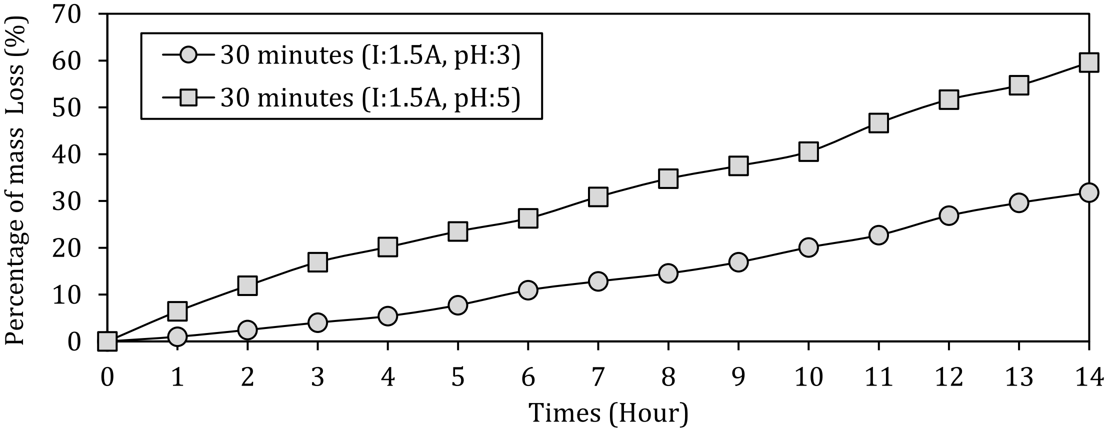

Figure 13: CoNiFe nanoparticles wear loss percentages as electrolyte pH increases.

In order to compare the erosion wear rate on similar coated substrates (30-min coating, pH 3) prepared at current intensity, 1.0 A, 2.0 A and 3.0 A current were chosen as distinctive settings. As illustrated in figure 12, it can be observed that there is a significant marginal mass loss between all current intensity chosen as the difference range between 5% of mass loss especially at longer duration of 11-14 hours of slurry operating period.

It is worth highlighting that as electrolyte pH increases; the percentage of mass loss increases from pH 3 to 5, resulting in a denser network of micro-cracks, where some of them penetrate through the thickness of coating (Figure 13). These cracks create pathways for degradation, which would translate into enhanced mass loss during corrosion or mechanical wear (Wu et al. 2014). The 30-min coating (1.5A, pH 3) substrate shows the lowest reduction in erosion while 30-min coating (1.5A, pH 5) shows the highest reduction in erosion as shown in figure 13. CoNiFe nanoparticles coating is a promising material for mechanical applications such as pipelines, valves, and drilling equipment due to their excellent corrosion resistance. Several studies done using cobalt and nickel-based alloy coating show good corrosion resistance results. Fu et. al reported Ni–Fe–Co–P coatings modified with CeO_2 nanoparticles demonstrate superior corrosion resistance in NaCl media (Fu et al. 2019) . Additionally, copper substrate electrodeposited with CoCrFeMnNi high entropy alloy (HEA) coating layers exhibit corrosion current densities as low as 0.0525 $\mu A/cm^2$, almost 44 times improvement against uncoated copper substrates in NaCl solution (Yoosefan et al. 2022). Ganji M. et. al reported the optimum Ni–Fe–TiC coating was obtained at the current density (J) of 30 mA/cm2, duty cycle of 60%, frequency (f) of 20 Hz and 2 g/L concentration of TiC nanoparticles. The optimum coating increased the corrosion potential from -0.675 V to -0.332 V and decreased the corrosion current density from 157.200μA/cm2 to 0.790μA/cm2 (Ganji et al. 2022).

4.0 CONCLUSION

From the results, it is determined that the deposition time, current intensity, and electrolyte pH all played major roles in determining coating homogeneity, which may have a direct impact on the performance of CoNiFe nanoparticles coating in terms of hardness, surface roughness, and slurry erosion wear. 30-min coating is sufficient to produce a full coating of CoNiFe nanoparticles coating. Surface hardness of the coated mild steel substrate was improved after being coated with CoNiFe nanoparticles coating. The increment of the deposition time increased the surface hardness of the coated mild steel substrates. The lowest surface roughness value, Ra recorded was 2.667 µm in the coated mild steel prepared at 30-min coating. An increasing trend in surface roughness was observed with higher current (3.074 µm) and pH levels (3.213 µm), compared to the standard 30-minute coating at 1.5 A and pH 3 (2.667 µm), indicating that both parameters contribute to rougher surfaces. On the other hand, less coating mass loss was produced from the lower surface roughness of the coated substrate during slurry erosion wear test. The existence of voids on coating surface showed the higher mass loss compared to the agglomerate coated surface. The results also explain the high hardness of coating deposited for 45 minutes at 320.68 HV, ~53% higher than the hardness of uncoated mild steel substrates. This high hardness of coating provides better erosive wear resistance behaviour. Overall, increased in deposition time, and current resulted in higher coating hardness. This showed that the coating could be applied in mechanical applications such as coating for pipelines, valves, and drilling equipment with prolong wear failure duration.

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REFERENCES

Del Giudice, M. E., Sharafkhani, M., Di Nardo, M., Murino, T., & Leva, M. C. (2024). Exploring safety of machineries and training: An overview of current literature applied to manufacturing environments. Processes, 12(4), 684.

Ebrahimi, F., & Ahmed, Z. (2003). The effect of current density on properties of electrodeposited nanocrystalline nickel. Journal of Applied Electrochemistry, 33, 733-739.

Fan, Q. (2025). High-temperature alloys in aerospace applications and future innovations. Highlights in Science, Engineering and Technology, 125, 296-302.

Farooq, S. A., Raina, A., Mohan, S., Singh, R. A., Jayalakshmi, S., & Irfan Ul Haq, M. (2022). Nanostructured coatings: Review on processing techniques, corrosion behaviour and tribological performance. Nanomaterials, 12(8), 1323.

Fu, X., Ma, W., Duan, S., Wang, Q., & Lin, J. (2019). Electrochemical corrosion behavior of Ni-Fe-Co-P alloy coating containing nano-CeO2 particles in NaCl solution. Materials, 12(16), 2614.

Ganji, M., Yousefnia, H., Seyedraoufi, Z., & Shajari, Y. (2022). The corrosion behavior of Ni-Fe and Ni-Fe-TiC nanoparticles deposited using pulse electrodeposition on low carbon steel. Journal of the Australian Ceramic Society.

Habib, S., Shakoor, R., & Kahraman, R. (2021). A focused review on smart carriers tailored for corrosion protection: Developments, applications, and challenges. Progress in Organic Coatings, 154, 106218.

Hyie, K. M., Salleh, Z., Masdek, N. R. N. M., Taib, Y. M., & Kalam, A. (2019). Erosion wear and adhesive investigation of Co-Ni-Fe coated on mild steel. Materials Today: Proceedings, 16, 1983-1987.

Hyie, K. M., Zabri, M. Z., Roseley, N. R. N., & Masdek, N. R. N. M. (2016). Effect of deposition time on wear and corrosion performance of Co–Ni–Fe alloy coated mild steel. Journal of Materials Research, 31(13), 1848-1856.

Ige, O., Umoru, L., Olorunniwo, O., & Adeoye, M. (2020). Erosion corrosion in the oil and gas industry: A review.

Jiang, S., Guo, Z., Liu, G., Gyimah, G. K., Li, X., & Dong, H. (2017). A rapid one-step process for fabrication of biomimetic superhydrophobic surfaces by pulse electrodeposition. Materials, 10(11), 1229.

Julka, S., Ansari, M. I., & Thakur, D. G. (2016). Effect of pH on mechanical, physical and tribological properties of electroless Ni-P-Al2O3 composite deposits for marine applications. Journal of Marine Science and Application, 15, 484-492.

Khanlari, K. (2015). Design of experiment of a novel cermet coating sprayed with the HVAF technology (Master's thesis). Tampere University of Technology, Finland.

Kim, Y., Seong, W. M., & Manthiram, A. (2021). Cobalt-free, high-nickel layered oxide cathodes for lithium-ion batteries: Progress, challenges, and perspectives. Energy Storage Materials, 34, 250-259.

Klarstrom, D., Crook, P., & Sharif, A. (2017). Cobalt alloys: Alloying and thermomechanical processing. In Reference module in materials science and materials engineering. Elsevier.

Liu, T., Ji, B., Wu, Y., Liu, Z., & Wang, W. (2022). Effects of the pH value on the electrodeposition of Fe–P alloy as a magnetic film material. The Journal of Physical Chemistry C, 126(36), 15472-15484.

Nan, X., Wang, F., Xin, S., Zhu, X., & Zhou, Q. (2023). Effect of process parameters on electrodeposition process of Co-Mo alloy coatings. Coatings, 13(4), 665.

Narváez, M., Cruzatty, C., Valencia, E., Hidalgo, V., Luo, X., Torres, A., Erazo, J., Altamirano, G., & Cando, E. (2023). Modeling of solid particle erosion for a water–sand impingement system using OpenFOAM. Coatings, 13(12), 2080.

Resali, N. A., Hyie, K. M., Abdullah, W. N. R., Ghani, M., & Kalam, A. (2013). The effect of bath pH on the phase formation of ternary Co-Ni-Fe nano-coatings. Applied Mechanics and Materials, 391, 9-13.

Roseley, N. R. N., Hyie, K. M., Masdek, N. R. N., Yussoff, N. S., & Abu, M. R. (2022). Evaluation of corrosion and erosive wear behaviour of Co-Ni-Fe coating deposited by electrodeposition method. Jurnal Tribologi, 34, 56-68.

Safavi, M. S., & Walsh, F. C. (2021). Electrodeposited Co-P alloy and composite coatings: A review of progress towards replacement of conventional hard chromium deposits. Surface and Coatings Technology, 422, 127564.

Saraloğlu Güler, E., Karakaya, İ., & Konca, E. (2014). Effects of current density, coating thickness, temperature, pH and particle concentration on internal stress during Ni–MoS2 electrocodeposition. Surface Engineering, 30(2), 109-114.

Siegel, J., Kvítek, O., Kolská, Z., Slepička, P., & Švorčík, V. (2012). Gold nanostructures prepared on solid surface. In Metallurgy–Advances in materials and processes (pp. 43-70). InTech.

Tientong, J., Thurber, C. R., D'Souza, N., Mohamed, A., & Golden, T. D. (2013). Influence of bath composition at acidic pH on electrodeposition of nickel-layered silicate nanocomposites for corrosion protection. International Journal of Electrochemistry, 2013(1), 853869.

Wang, D., Li, F., Shi, Y., Liu, M., Liu, B., & Chang, Q. (2021). Optimization of the preparation parameters of high-strength nickel layers by electrodeposition on mild steel substrates. Materials, 14(18), 5461.

Wu, W., Eliaz, N., & Gileadi, E. (2014). The effects of pH and temperature on electrodeposition of Re-Ir-Ni coatings from aqueous solutions. Journal of The Electrochemical Society, 162(1), D20.

Yoo, B., Hernandez, S., Park, D.-Y., & Myung, N. (2006). Electrodeposition of FeCoNi thin films for magnetic-MEMS devices. Electrochimica Acta, 51(28), 6346-6352.

Yoosefan, F., Ashrafi, A., & Monir Vaghefi, S. M. (2022). Microstructure and corrosion properties of electrodeposited CoCrFeMnNi high entropy alloy coatings. Frontiers in Materials, 9, 891011.

Zabri, M. Z., Masdek, N., Mardziah, C. M., & Ahmad, N. (2024). Surface properties and characterisation of cobalt-nickel-iron alloy coating on mild steel for engineering applications. Nigerian Journal of Technological Development, 21(4), 159-167.

Zabri, M. Z., Masdek, N. R. N., & Hyie, K. M. (2022). A brief review of Co-Ni-Fe nanocrystalline coatings: Properties and their applications. Current Topics in Electrochemistry, 24, 85-99.

Zabri, M. Z., Masdek, N. R. N. M., & Syehab, M. A. M. (2025). Understanding of heat treatment on the durability of cobalt alloy thin film coated on mild steel. Journal of Mechanical Engineering, 22(2), 133-147.

Zabri, M. Z., Nik Masdek, N. R., & Hyie, K. M. (2023). The effect of cobalt alloy nanocrystalline coating on tensile properties and surface performance of mild steel. Journal of Mechanical Engineering SI, 12(1), 21-43.