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Research Article

Investigation on Wear and Corrosion Behavior of Cu, Zn, and Ni Coated Corten Steel

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Corten steel is a low-carbon alloy steel. It is widely used in architecture, the transport sector, and industrial applications, where the steel is exposed to harsh environments. It is very much sought after due to its auto protection from corrosive environments through the formation of patina (rust). The specialty of patina formed on the corten steel is that it can self-heal itself and stop the spreading of corrosion. Generally, steels are given protective coatings to enhance resistance to corrosion, wear, abrasion, etc. One of the popular protective coating techniques is electroplating. In this study, the effect of electroplating of copper (Cu), zinc (Zn), and nickel (Ni) on the wear and corrosion behavior of Corten ASTM A242 grade steel is investigated. It was observed that the Cu coating yielded poor corrosion and wear protection performance. The Zn coating exhibited a moderate improvement. The Ni electroplating produced excellent results and, the wear and corrosion resistance was improved in the corten steel. Thus, when compared with Cu, Zn, and Ni coatings, the Ni-coated corten steel is an ideal candidate in applications where there is a need for good resistance to wear, abrasion, and corrosion.

1. Introduction

The corten steel belongs to the family of weathering steels. The corten steel's uniqueness lies in its ability to instantaneously form a stable rust layer called as patina. This patina gives corten steel the aesthetically pleasing appearance and also makes it immune to corrosion. The rust formed on the corten steel prevents further corrosion of the underlying corten steel, by forming an impervious passivation layer. Furthermore, corten steel has good combination of mechanical properties with minimal alloying in the low alloyed steels segment. Since it has good weight to strength ratio, it is widely used in fabrication of railway coaches, transport industry, bridges, structures, etc. The corten steel is the work horse of the railway coach building industry. Corten steel is inherently capable to serve in harsh environments and climatic conditions. The versatility of corten steel lies in its ability to be welded, formed, and undergo processing and heat treatments, and thus its properties could be engineered to produce various products, equipment, structures etc.

The presence of Ni in corten steel makes it unique among the weathering steel, as the Ni present in it enhances the corrosion resistance as observed by other investigators [1]. The uniqueness of corten steel lies in the proper combination of alloying elements in it. Several investigators have observed that, if the quantity of elements like Mn increases, the corrosion rate will increase and also the structure of the rust formed will be poor [2, 3]. Ni-based coatings through electroplating route has enhanced the wear and corrosion resistance of the steel substrate and mechanical properties, as discussed elsewhere [4–8]. Copper, as a corrosion and wear resistant coating, is effective only when coupled with elements like Cr as discussed elsewhere [9–11]. The Ni coating is nonpervious to corrosion than the Cu coating as observed by other investigators [12]. Several investigators have tried to explore the corrosion behavior of corten steel and other weathering steels and observed that the corten steel possesses good immunity to corrosion [13–16]. The Zn-based coatings provide good immunity in salty environments as discussed elsewhere [17, 18]. The Zn-based coating offers good corrosion resistance but the passivation layer shall be porous and hence likely to form pitting as discussed by Protsenko and Danilov [19]. The coating of Cu and Ni imparts immunity from wear, stress corrosion cracking, erosion, abrasion, etc. as studied by other investigators [20]. Most of the investigators have studied coating of other steels through techniques other than electroplating, like jet electrodeposition and dipping, for studying corrosion behavior, ballistic response, etc. [17–20]. There is scant work reported in literature on the electroplating behavior in corten steel and thus, necessitating this investigation.

2. Materials and Methods

The Corten ASTM A242 Grade Steel of 3 mm thickness was taken for this investigation. The composition of the corten steel was determined using a vacuum spark spectrometer. The micro Vickers hardness test was carried out conforming to ASTM E384—10e2 using Wilson Wolpert micro Vickers hardness testing machine on the Corten steel with 0.5 kg load and dwell of 5 sec. The metallurgical specimens are prepared by polishing with various grades of emery paper, polished with lavigated alumina (0.0013 μm particle size) and final polishing was done using diamond polishing compound (0.25 μm particle size) and then etched with Nital. The microstructural analysis was performed using a Zeiss Axio Scope optical microscope. The Cu, Zn, and Ni coating were done individually on corten steel in AK Finishing Technologies, Chennai, India. The scratch test was performed using Ducom, Bangalore, India, scratch tester. The scratch test was carried out with a Rockwell diamond stylus indenter of 120 degrees, length of 45 mm, friction accuracy of 0.1 N for a depth range of 0–300 mm, and a working load of 5 N. The surface roughness (Ra) was measured using a Mitutoyo roughness tester. The coating thickness was measured using an optical microscope scale. The bend test was performed using a universal testing machine (UTM). The corrosion test was carried out in a salt spray setup for 48 hours conforming to ASTM B117. The corrosion test setup was maintained at a temperature of $33 \pm 1^{\circ}$C with 5% NaCl. The weight loss was measured every 12 hours. The surface morphology of the corroded corten steel was studied using Jeol—scanning electron microscope (SEM). The elemental composition of the corroded surface was determined using the energy dispersive spectroscopy (EDS) attached with the SEM machine. The dry pin on disk wear test were carried out on the electroplated specimens with an applied load of 20 N, sliding velocity of 1 m/sec, and sliding distance of 300 m, at 637 rpm; for 300 seconds.

3. Results and Discussion

3.1. Chemical Composition. The elemental composition conforms to Corten Steel—ASTM 242 and is shown in Table 1. The presence of Nickel and chromium contributes to its inherent corrosion resistance. The unique blend of alloying elements gives the corten steel good mechanical properties and corrosion resistance. Furthermore, due to its low alloying content, it is a cheap deal over its functionality.

3.2. Microstructure. The microstructure shows mill normalized condition with uniform grains of pearlite in ferrite matrix. The rolling bands are observed along the longitudinal direction of the sheet. The grain size corresponds to ASTM grain size No; as per ASTM E-112. The average grain size measured as grain size No; 6 as per the standard. No stringers observed between the grain flow. The microstructure shows resolved grain boundaries and the precipitated pearlite between the grain boundaries which is shown in Figure 1. The grains of pearlite show no elongated grains.

3.3. Hardness Test. The microhardness of the corten steel in pristine condition and electroplated condition is shown in Figure 2. The Cu-coated corten steel specimens exhibited an increase of around 197.1% in microhardness when compared with the uncoated corten steel. Similarly, the Ni-coated specimens showed an increase of around 400.2% in microhardness. However, the Zn-coated specimens showed a decrease of around 47.6% in microhardness. This behavior vindicates the nature of the coating in terms of density of the coating. From these observations, it can be inferred that the Ni coating has potential to resist wear and abrasion, whereas the Zn coating has the least wear resistance.

3.4. Coating Thickness. When comparing the macrostructure images in Figure 3, and coating thickness measurements in Figure 4, the Zn coating thickness is observed to be considerably more than Cu and Ni coating. The Cu coating has the least thickness and the Ni coating higher than Cu; and the Zn coating has the highest thickness. This nonuneven distribution of coating thickness among Cu, Zn, and Ni, shall be attributed to the electro chemical reaction and the reduction potential of the respective elements involved in the electroplating process.

From (1), it could be observed that the oxygen forms hydroxyl ions when reacted with water during electroplating. The following reactions take place in nickel, copper, and zinc; equations (2)–(4), where the respective metal hydroxides are formed on the cathode (carton steel) during electro plating, as discussed elsewhere [4, 21, 22]. The reduction potential of copper is 0.337 V, nickel is −0.25 V, and zinc is −0.7628 V. By virtue of their reduction potential, zinc has greater reduction potential and hence easily gets deposited on the cathode (corten steel), whereas copper has least deposition rate and the deposition rate of nickel is moderate. This is responsible for their respective thickness of coating through the electroplating process. Hence, Zn in the presence of iron (Fe) tends to produce thick coating, as observed by other investigators [23].

Table 1: Chemical composition of corten steel (conforming to ASTM 242).

Elements	C	Si	Mn	P	S	Cr	Ni	Mo	V	W	Ti	Al	C	N	Fe
Weight (%)	0.108	0.262	0.366	0.092	0.013	0.555	0.188	0.005	0.003	<0.01	0.003	0.030	0.005	0.0341	Remainder

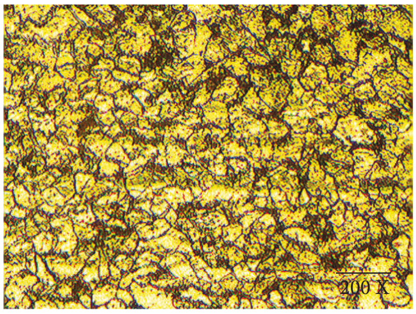


Figure 1: Microstructure of corten steel.

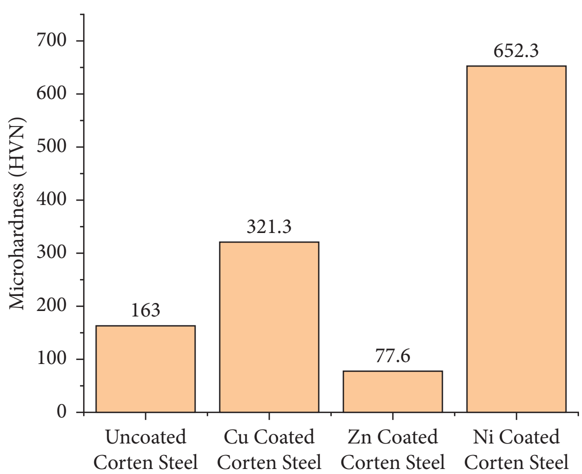


Figure 2: Microhardness of uncoated and coated corten steel specimen.

$$\frac{1}{2o_2} + 2H_2O + 2E - \longrightarrow 2OH \quad (1)$$

$$Ni^{2+} + 2OH^{-} \longrightarrow Ni(OH)_2 \quad (2)$$

$$Cu^{2+} + 2OH^{-} \longrightarrow Cu(OH)_2 \quad (3)$$

$$Zn^{2+} + 2OH^{-} \longrightarrow Zn(OH)_2 \quad (4)$$

3.5. Scratch Test. The scratch test is carried out to determine the vulnerability of the coating to abrasion. From Figure 5, it is clear that Zn shows a poor performance, and Cu has slightly better scratch resistance. However, Ni coating offers good scratch resistance to the underlying corten steel and thus proves that the coating is coherent and could resist abrasions and shall be durable.

3.6. Surface Roughness (R_a). The Cu coating produces a rough finish, followed by Ni-coated corten steel surface and is shown in Figure 6. The Zn-coated corten steel surface exhibits around half of the roughness R_a values when compared with other two coatings. When compared with Cu and Ni, the Zn coating produces a smooth surface with lower R_a value.

3.7. Adhesive Bend Test. A gradual linear increase in the adhesive bend strength is observed in Figure 7. This trend indicates that there is not much effect of coating on the ultimate bending strength. Furthermore, it is obvious from the Figure that the adhesion of the coating is good in Ni when compared with Cu and Zn. This behavior shall enhance the durability of the coating in functional field applications.

3.8. Corrosion Test. The weight loss due to the corrosion of Cu, Zn, and Ni is very much low when compared with the uncoated corten steel and is shown in Figure 8. This indicates that the coatings offer the corten steel surface, immunity from corrosion [24–27]. Among the three coatings, Ni had the least corrosion-induced material weight loss. The corrosion rate of Cu spiked when compared to the uncoated corten steel due to the Fe surface catalyzed reaction of Cu, which causes accelerated corrosion. The Ni-coated carton steel exhibited least corrosion rate compared to other corrosion coupons. Zn exhibited a slightly higher corrosion rate than the Ni-coated carton steel coupons. The reason behind the minimal corrosion rate of Ni-coated carton steel is its strong bonding with the substrate and its capability to plug the pores and holes in the surface of the carton steel, and thereby sealing all paths from corrosion attack.

Furthermore, the Ni has strong affinity towards Fe and hence the bonding between the corten steel substrate is good. However, in the case of Cu, this affinity is less and hence the bonding is poor, as discussed by Singh and Singh [28].

The Fe in the corten steel substrate surface triggers the chemical reduction of Cu. This surface catalyzed chemical reduction reaction is shown in (5) as formulated by investigators elsewhere [20].

$$Cu^{2+}_{(aq)} + Fe_{(s)} \longrightarrow Cu_{(s)} + Fe^{2+}_{(aq)} \quad (5)$$

It can be observed from (1), that the chemical reduction reaction results in poor adherence, and a less dense coating of Cu on the corten steel.

Zn exhibits a spontaneous dense passivation layer in the presence of Fe in the corten steel substrate, which imparts corrosion resistance to the substrate as discussed by other investigators [23].

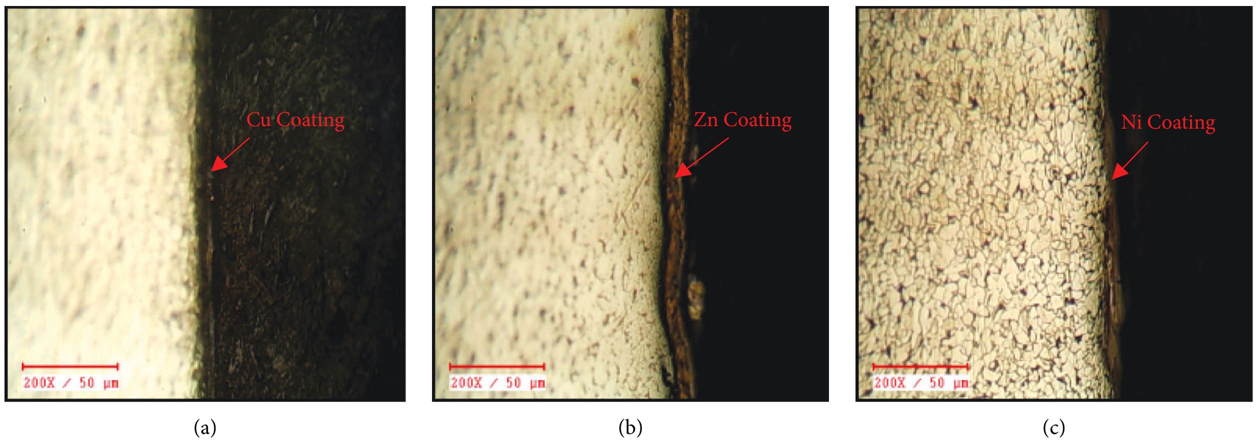


FIGURE 3: Macrostructure of electroplated corten steel (a) Cu coated (b) Zn coated (c) Ni coated.

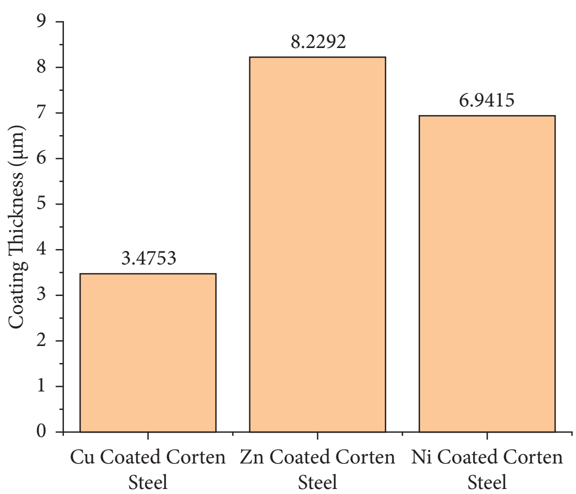


FIGURE 4: Coating thickness of electroplated corten steel.

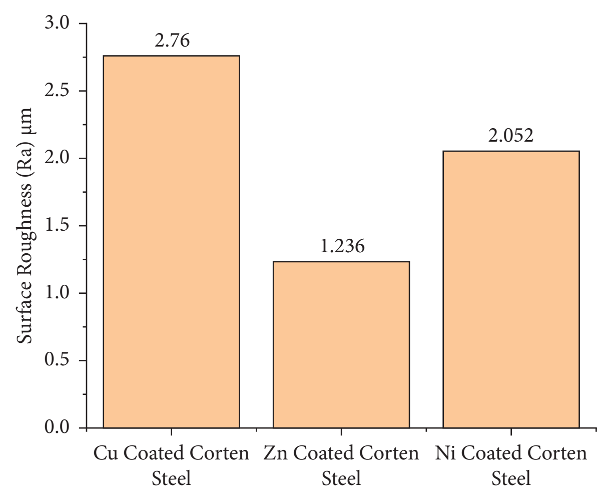


FIGURE 6: Roughness (R_a) of electroplated corten steel.

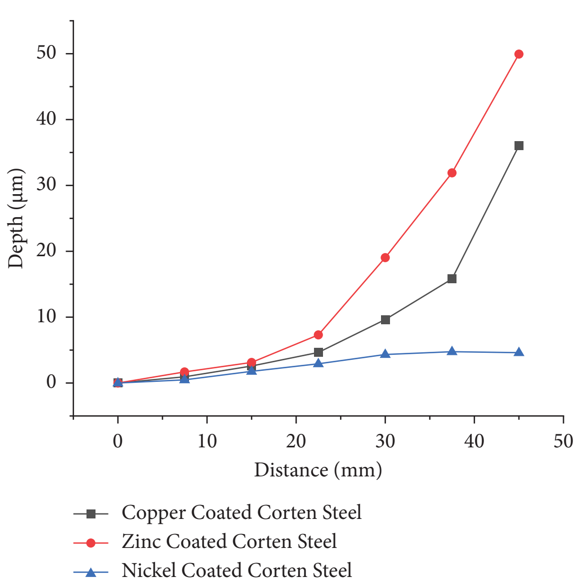


FIGURE 5: Scratch penetration depth of electroplated corten steel.

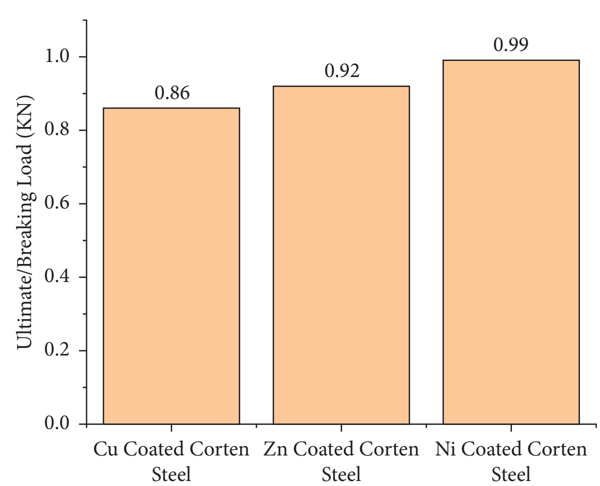


FIGURE 7: Adhesive bend strength of electroplated corten steel.

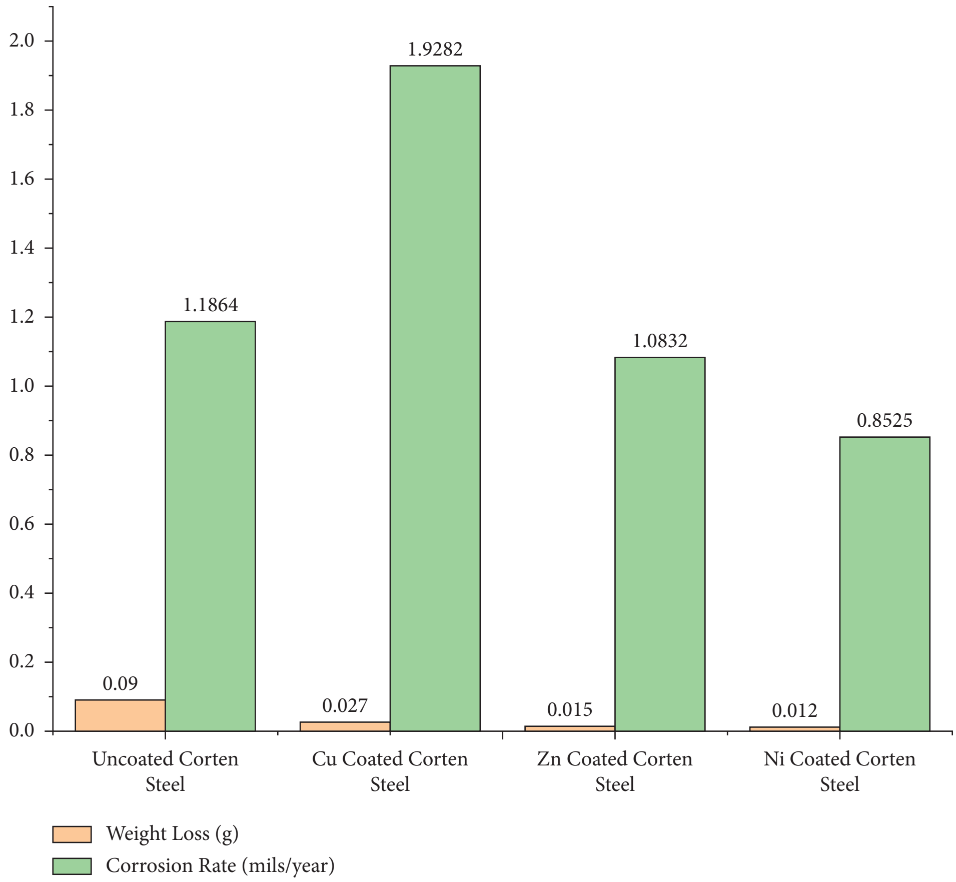
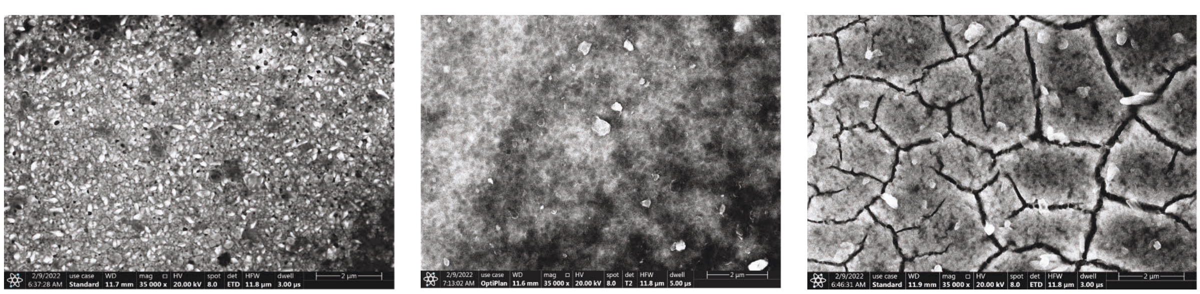


Figure 8: Salt spray test result of uncoated and coated corten steel.



(a) (b) (c)

Figure 9: SEM surface morphology images of electroplated corten steel (a) Cu coated (b) Zn coated (c) Ni coated.

The SEM image in Figure 9(a) shows numerous pores in the Cu-coated layer leading to pitting and increased corrosion rate. The presence of pores in the Cu coating leads to leaching out of Fe and thus aggravating the corrosion and it is evident from the EDS report shown in Figure 10(a).

The SEM image in Figure 9(b) shows a uniform coating of Zn and a dense passivation layer formation, which protects the substrate from corrosion and is visible from the EDS report in Figure 10(b).

The SEM image in Figure 9(c) shows a dense passivation layer formation upon exposure to corrosive medium, which leads to good corrosion resistance and is seen from the elemental spectrum in EDS report shown in Figure 10(c), as observed elsewhere [29]. The Ni coating was effective as it was able to form a coherent layer which seals the pores in the corten steel substrate and prevents outward migration of elements from the substrate as discussed elsewhere [30–33]. The presence of Mo in the Corten steel matrix works synergistically with Ni coating to prevent growth of pits during the formation of the passivation layer as discussed by other investigators [34].

3.9. Wear Test. The inherent behavior of Zn upon electroplating, is to reduce the ductility of the steel and form incoherent coating, this in turn makes the corten steel susceptible to wear as observed by other investigators [35]. This shall be attributed to the higher wear induced weight loss of Zn-coated corten steel than the Cu and Ni-coated substrates, as shown in Figure 11.

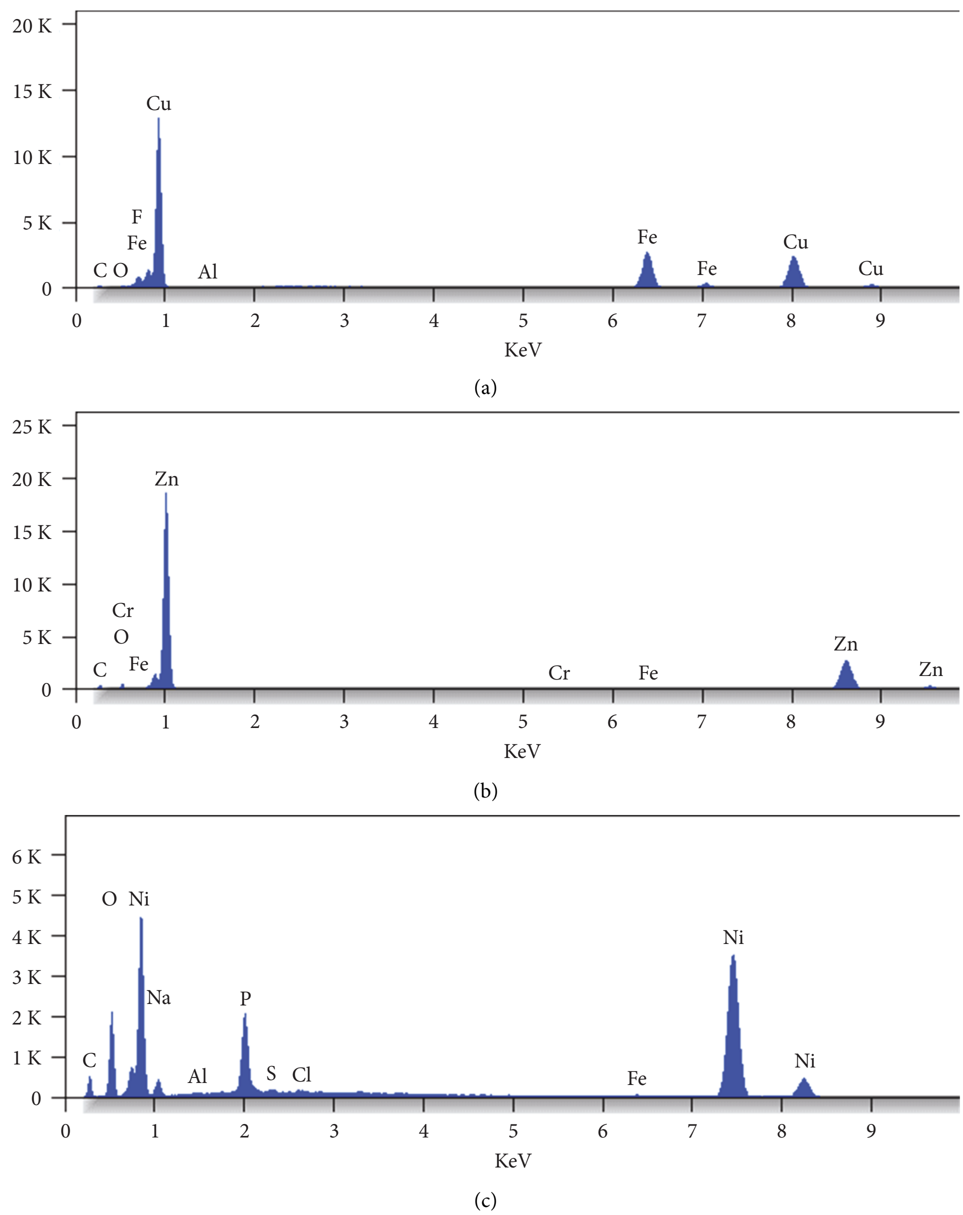


Figure 10: Energy dispersive spectroscopy (EDS) report of (a) Cu electroplated corten steel, (b) Zn electroplated corten steel, and (c) Ni electroplated corten steel.

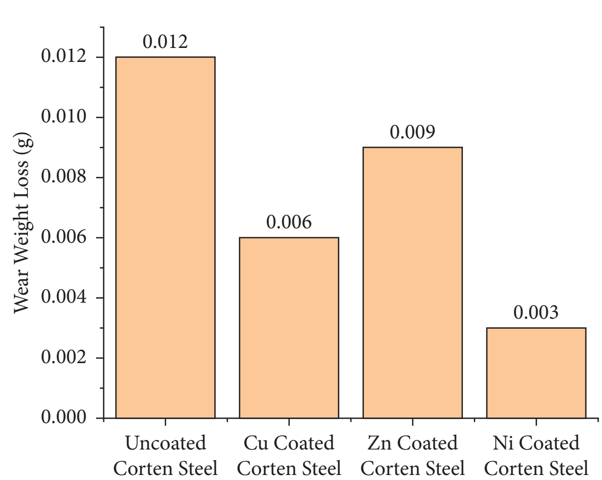


Figure 11: Wear test weight loss of uncoated and coated corten steel.

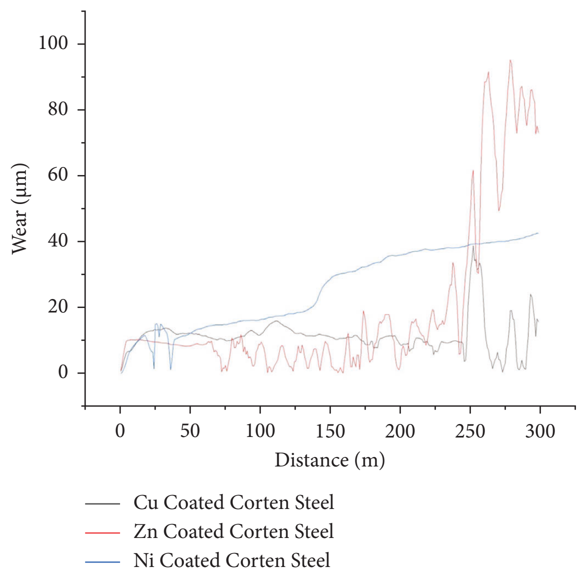


FIGURE 12: Wear rate of electroplated corten steel.

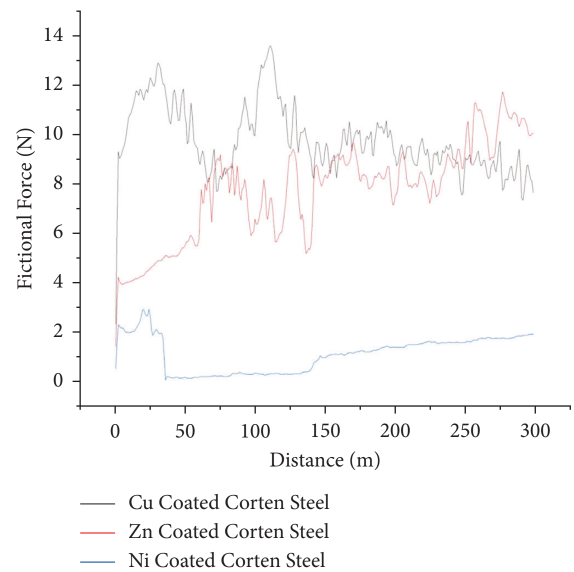


FIGURE 14: Wear frictional force of electroplated corten steel.

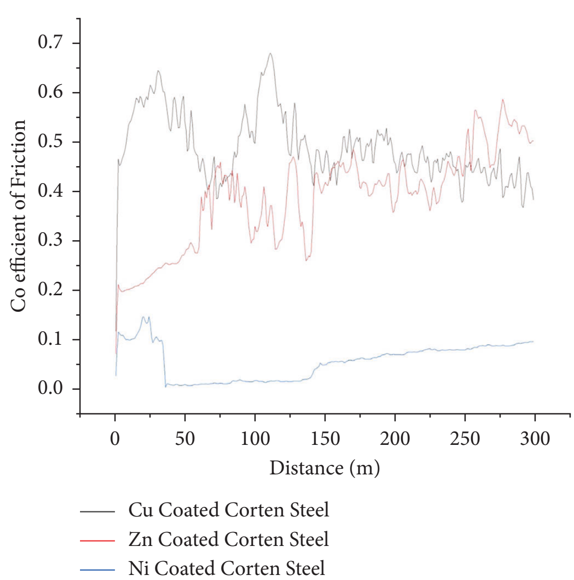


FIGURE 13: Coefficient of friction of electroplated corten steel.

The wear rate of the three electroplated specimens is shown in Figure 12, where it is observed that Zn exhibits a spike in wear rate; Cu has a steady trend in wear rate; and Ni has a moderate wear rate. The coefficients of friction (COF) of the three electroplated specimens are shown in Figure 13. The COF of Ni-coated corten steel specimens is less when compared with Cu and Zn-coated corten steel specimens. The low COF of Ni indicates its inherent immunity to wear and vice versa in the case of Cu and Zn-coated corten steel specimens. A similar trend is observed in the Figure 14, which depicts the wear frictional force during the wear test on the Cu, Zn, and Ni electroplated corten steel specimens. As the frictional force is lower in the Ni-plated surface, the wear also is low.

4. Conclusion

Corten steel is inherently resistant to corrosion and wear, due to its unique blend of alloying elements. As it is cheap and is the staple raw material for architectural applications, in this investigation, an effort has been taken to enhance its corrosion and wear resistance and also improve its durability, through electroplating. This study yielded good insight into the mechanism behind the improvement of properties by the electroplating of corten steel with Cu, Zn, and Ni. The Ni-coated corten steel specimens exhibited the lowest corrosion rate of 0.8525 mils/year and wear weight loss of 0.003 g, when compared with Cu and Zn-coated specimens. Ni was found to be the ideal coating that can impart resistance to corten steel–ASTM 242 from wear, abrasion, and corrosion.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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References

[1] C. Chiavari, E. Bernardi, C. Martini, F. Passarini, A. Motori, and M. C. Bignozzi, “Atmospheric corrosion of Cor-Ten steel with different surface finish: accelerated ageing and metal release,” *Materials Chemistry and Physics*, vol. 136, no. 2–3, pp. 477–486, 2012.

[2] J. Jia, X. Cheng, X. Yang, X. Li, and W. Li, “A study for corrosion behavior of a new-type weathering steel used in harsh marine environment,” *Construction and Building Materials*, vol. 259, Article ID 119760, 2020.

[3] V. K. Bupesh Raja, K. Palanikumar, R. Rohith Renish, A. N. Ganesh Babu, J. Varma, and P. Gopal, “Corrosion resistance of corten steel—a review,” *Materials Today Proceedings*, vol. 46, pp. 3572–3577, 2021.

[4] C. s. Liu, F. h. Su, and J. z. Liang, “Fabrication of Co–Ni–P film with excellent wear and corrosion resistance by electroplating with supercritical CO2 emulsion,” *Transactions of Nonferrous Metals Society of China*, vol. 28, no. 12, pp. 2489–2498, 2018.

[5] C. Y. Bai, J. L. Lee, T. M. Wen, K. H. Hou, M. S. Wu, and M. D. Ger, “The characteristics of chromized 1020 steel with electrical discharge machining and Ni electroplating pretreatments,” *Applied Surface Science*, vol. 257, no. 8, pp. 3529–3537, 2011.

[6] H. H. Zhou, Z. W. Liao, C. X. Fang et al., “Pulse electroplating of Ni-W-P coating and its anti-corrosion performance,” *Transactions of Nonferrous Metals Society of China*, vol. 28, no. 1, pp. 88–95, 2018.

[7] T. M. Meißner, C. Oskay, A. Bonk et al., “Improving the corrosion resistance of ferritic-martensitic steels at 600°C in molten solar salt via diffusion coatings,” *Solar Energy Materials and Solar Cells*, vol. 227, Article ID 111105, 2021.

[8] D. J. Raj, V. K. B. Raja, T. S. Savan, and S. Babu, “Development of novel tricoated CuNiCr filler for welding weathering steel,” *AIP Conference Proceedings*, vol. 2311, 2020.

[9] C. A. Huang, C. K. Lin, and Y. H. Yeh, “The corrosion and wear resistances of magnesium alloy (LZ91) electroplated with copper and followed by 1 μm-thick chromium deposits,” *Thin Solid Films*, vol. 519, no. 15, pp. 4774–4780, 2011.

[10] C. A. Huang, C. K. Lin, and Y. H. Yeh, “Increasing the wear and corrosion resistance of magnesium alloy (AZ91D) with electrodeposition from eco-friendly copper- and trivalent chromium-plating baths,” *Surface and Coatings Technology*, vol. 205, no. 1, pp. 139–145, 2010.

[11] J. R. Deepak, V. K. Bupesh Raja, and G. S. Kaliaraj, “Mechanical and corrosion behavior of Cu, Cr, Ni and Zn electroplating on corten A588 steel for scope for betterment in ambient construction applications,” *Results in Physics*, vol. 14, Article ID 102437, 2019.

[12] M. Weinstein, C. Falconer, W. Doniger et al., “Environmental degradation of electroplated nickel and copper coated SS316H in molten FLiNaK salt,” *Corrosion Science*, vol. 191, Article ID 109735, 2021.

[13] Abdel Halim, K. S., Ramadan, M., Sherif, E. S. M. et al., “Enhancement of surface and interface properties of low carbon steel by hybrid ZnO and NiO nanoparticles reinforced iin coating. Crystals,” *Surface and Coatings Technology*, vol. 12, 332, 2022, 2016.

[14] Q. Zhang, Y. Feng, Z. Chen et al., “Preparation and corrosion resistance of Ni-W-cf composite coating on P110 steel,” *Coatings*, vol. 12, no. 2, p. 231, 2022.

[15] C. Barile, C. Casavola, G. Pappalettera, and V. P. Kannan, “Designing a deep neural network for an acousto-ultrasonic investigation on the corrosion behaviour of CORTEN steel,” *Procedia Structural Integrity*, vol. 37, pp. 307–313, 2022.

[16] M. Rohmah, P. A. Paristiawan, and T. B. Romijarso, “Effect of forging load and heat treatment process on the corrosion behavior of A588-1% NI for weathering steel application in a marine environment,” vol. 26, no. 2, pp. 237–248, 2022.

[17] M. M. Karimi Azar, H. Shooshtari Gugtapeh, and M. Rezaei, “Evaluation of corrosion protection performance of electroplated zinc and zinc-graphene oxide nanocomposite coatings in air saturated 3.5 wt. % NaCl solution,” *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 601, Article ID 125051, 2020.

[18] W. Wu, R. Chen, Z. Yang, Z. He, Y. Zhou, and F. Lv, “Corrosion resistance of 45 carbon steel enhanced by laser graphene-based coating,” *Diamond and Related Materials*, vol. 116, Article ID 108370, 2021.

[19] V. S. Protsenko and F. I. Danilov, “The corrosion-protective traits of electroplated multilayer zinc-iron-chromium deposits,” *Metal Finishing*, vol. 108, no. 5, pp. 28–32, 2010.

[20] Y. Reda, A. M. El-Shamy, and A. K. Eessaa, “Effect of hydrogen embrittlement on the microstructures of electroplated steel alloy 4130,” *Ain Shams Engineering Journal*, vol. 9, no. 4, pp. 2973–2982, 2018.

[21] J. Gong and G. Zangari, “Increased metallic character of electrodeposited Mn coatings using metal ion additives,” *Electrochemical and Solid-State Letters*, vol. 7, no. 9, pp. 91–94, 2004.

[22] Y. I. Supriyatna, R. Noviyana, E. G. Suka, B. N. Hidayah Kambuna, S. Sumardi, and Sudibyo, “Influence of current density in Cu-Mn electroplating of AISI 1020 steel corrosion rate,” *Materials Today Proceedings*, vol. 44, pp. 3289–3295, 2021.

[23] Y. I. Choi, E. S. Shin, K. Kuroda, M. Okido, and C. J. Park, “Improved surface morphology and corrosion resistance for galvannealed coatings by pre-electroplating iron,” *Corrosion Science*, vol. 58, pp. 152–158, 2012.

[24] M. A. Abdulrahaman, O. K. Abubakre, S. A. Abdulkareem, J. O. Tijani, A. Aliyu, and A. S. Afolabi, “Effect of coating mild steel with CNTs on its mechanical properties and corrosion behaviour in acidic medium,” *Advances in Natural Sciences: Nanoscience and Nanotechnology*, vol. 8, no. 1, Article ID 15016, 2017.

[25] S. Kordzangeneh, S. Naghibi, and H. Esmaeili, “Coating of steel by alkyd resin reinforced with Al2O3 nanoparticles to improve corrosion resistance,” *Journal of Materials Engineering and Performance*, vol. 27, no. 1, pp. 219–227, 2018.

[26] H. Cheng, B. Xu, J. Zhao et al., “High-performance nickel coating on SLM 316L stainless steel processed by jet electrochemical machining and jet electrodeposition,” *Proceedings of the Institution of Mechanical Engineers - Part B: Journal of Engineering Manufacture*, vol. 236, no. 4, pp. 462–472, 2022.

[27] D. Chu, Z. Li, K. Yao et al., “Studying the strengthening mechanism and thickness effect of elastomer coating on the ballistic-resistance of the polyurea-coated steel plate,” *International Journal of Impact Engineering*, vol. 163, Article ID 104181, 2022.

[28] S. Singh and H. Singh, “Effect of electroplated interlayers on bonding mechanism of cold-sprayed copper on SS316L steel substrate,” *Vacuum*, vol. 172, Article ID 109092, 2020.

[29] H. H. Sheu, H. B. Lee, S. Y. Jian, C. Y. Hsu, and C. Y. Lee, “Investigation on the corrosion resistance of trivalent chromium conversion passivate on electroplated Zn–Ni alloy,” *Surface and Coatings Technology*, vol. 305, pp. 241–248, 2016.

[30] P. Niranatlumpong and H. Koiprasert, "Improved corrosion resistance of thermally sprayed coating via surface grinding and electroplating techniques," *Surface and Coatings Technology*, vol. 201, no. 3–4, pp. 737–743, 2006.

[31] Q. Zhao, S. Geng, G. Chen, and F. Wang, "Comparison of electroplating and sputtering Ni for Ni/NiFe2 dual layer coating on ferritic stainless steel interconnect," *Corrosion Science*, vol. 192, Article ID 109837, 2021.

[32] Y. Zhang, "Mechanical properties and corrosion resistance of pulse electrodeposited Ni-B/B4C composite coatings," *Surface and Coatings Technology*, vol. 421, 2021.

[33] Y. Li, P. Song, W. Wang, M. Lei, and X. Li, "Microstructure and wear resistance of a Ni-WC composite coating on titanium grade 2 obtained by electroplating and electron beam remelting," *Materials Characterization*, vol. 170, Article ID 110674, 2020.

[34] S. Mosayebi, M. Rezaei, and Z. Mahidashti, "Comparing corrosion behavior of Ni and ni-mo electroplated coatings in chloride mediums," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 594, Article ID 124654, 2020.

[35] T. Mehner, I. Scharf, P. Frint et al., "Hydrogen embrittlement of a quenching and partitioning steel during corrosion and zinc electroplating," *Materials Science and Engineering A*, vol. 744, pp. 247–254, 2019.