COBALT-FERROUS RATIOS FOR ENHANCED CORROSION AND WEAR RESISTANCE OF ELECTRODEPOSITED COATINGS ON 316 STAINLESS-STEELS

SAI PRASANNA KUMAR J.V[1*], SUNDHARESAN R[1], DOMINIK KRYSKA[2], ROBERT CEP[2], S P SAMAL[3*]

[1]Department of Mechanical Engineering, Vel Tech Rangarajan Dr, Sagunthala R&D Institute of Science and Technology, Avadi, 600062, India
drjvsaiprasannakumar@veltech.edu.in
sundaraero07@gmail.com

[2]Department of Machining, Assembly and Engineering Metrology, Faculty of Mechanical Engineering, VSB-Technical University of Ostrava, 70800 Ostrava, Czech Republic; robert.cep@vsb.cz

[3]Department of Biosciences, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai 602105, India. spsamal24@gmail.com

DOI: 10.17973/MMSJ.2025_03_2025009

drjvsaiprasannakumar@veltech.edu.in; spsamal24@gmail.com

ABSTRACT

This study investigates the enhancement of wear and corrosion resistance of 316 stainless steels through Co-Fe electrodeposited coatings at varying ratios (50:50, 75:25, 95:5). The 50:50 Co-Fe ratios produced a uniform, defect-free coating with a thickness of 35 µm and a body-centered cubic (BCC) microstructure. Electrochemical tests, including Tafel and Nyquist plots, revealed superior corrosion resistance for the 50:50 ratio, with a low corrosion rate of 0.0037 mm/year, a corrosion potential (Ecorr) of -259.534 mV, and a corrosion current density (Icorr) of 12.752 µA. Tribological evaluation indicated the highest wear resistance, with the longest wear time (1082 seconds) and the lowest coefficient of friction (0.29). These findings highlight the potential of Co-Fe coatings for aerospace and marine applications, particularly in components exposed to harsh mechanical and corrosive environments. The study also emphasizes the novelty of cyclic voltammetry as a precise method for optimizing electrodeposited coatings.

KEYWORDS

Electrochemical deposition, Wear Resistance, EIS, XRD patterns, FESEM, Cobalt Sulphate, Ferrous Sulphate, Tafel and Nyquist Plots.

1 INTRODUCTION

The use of protective coatings stands as a necessity for stainless-steel parts to improve their resistance against wear and corrosion especially during conditions of aerospace and marine applications. Scientists have investigated magnetron sputtering; friction stir processing and cathodic plasma electrolytic oxidation as different deposition methods to enhance material properties. The existing methods to protect stainless steel components face multiple disadvantages because they result in high production expenses, or they prove hard to expand or create gaps in their binding power when exposed to harsh mechanical extraction and corrosive environments.

This research works to improve Co-Fe electrodeposited coatings on 316 stainless steels by employing different compositions of cobalt and iron (50:50, 75:25, and 95:5). Electrodeposition served as the method because it allows the production of defect-free coatings with parameterized composition through uniform processes while maintaining economical practices. Previous investigations regarding Co-Fe coating corrosion-wear properties have shown insufficient research on systematic composition-based changes affecting corrosion resistance and electrochemical stability along with tribological characteristics.

The electrochemical corrosion behaviour of nanocrystalline (NC) materials is highlighted, showing that nano crystallization impacts corrosion processes differently based on the solubility of corrosion products: enhancing corrosion with soluble products but building protection against corrosion with insoluble products. NC materials enhance formation of compact passive films on the surface, enrich the concentration of passive elements such as Cr and Ti and modify the adsorption of ions. Self-healing characteristics also make the material resistant to localized corrosion attack. In general, nano crystallization enhances corrosion protection by altering the metal and alloy surface and passive layer properties [Liu 2010].

The corrosion and erosive wear performance of the Co-Ni-Fe layer electrodeposited on MS specimens after 30 min to 90 min suggested that the increment in the deposition time enhance the particle size, reduced porosity and improved density and homogeneity of the deposit. Coatings became harder than the substrate with the highest hardness of 383 Hv and the best corrosion protective ability after 90 minutes of deposition, which show weight loss of 48% less than the bare substrate. Erosive wear resistance enhanced when coating duration was eighteen coating cycles as it demonstrated weight loss of 22% of the 30-minute coating and only 1.70% of the 90-minute coating. The results imply that increased deposition times improve mechanical and protection properties of Co-Ni-Fe coatings [Roseley 2022].

The corrosion rates of the nanocrystalline CoFe alloy coatings electrodeposited on 304 stainless steel and AISI 1080 mild steel substrates have been studied. CoFe coatings synthesized in a sulphate bath with varying iron content were assessed for phase composition, crystallite size, and corrosion resistance. The highest microhardness (324.32 HV) and the smallest grain size were achieved with 2.76 g of Fe content on 1018 mild steel. The data obtained from potentiodynamic polarization tests indicated increased corrosion resistance for the CoFe coatings obtained on 304 stainless steels as compared to 1018 mild steel. Increasing iron content improved mechanical properties but also increased corrosion rates [Adull Manan 2017].

Cathodic plasma electrolytic oxidation (CPEO) coatings on 304 stainless steels were investigated for their morphology, microstructure, phase composition, hardness, and tribological behaviour. Coatings of 35 µm, 80 µm, and 180 µm thicknesses were produced, showing a two-layer structure: a loose outer layer of Fe_3O_4 and a compact inner layer containing $FeCr_2O_4$, $NiCr_2O_4$, Fe_3O_4, and FeO phases. The maximum hardness (1335 HV) was achieved in the compact layer. Tribological tests showed a significantly lower friction coefficient (as low as 0.1) and wear rate, with the 180 µm coating reducing wear by two orders of magnitude compared to untreated stainless steel. CPEO significantly enhanced the wear resistance of stainless steel [Jin 2013].

The effects of single-pass ultrasonic surface rolling (USR) on the wear resistance and hardness of AISI 316L stainless steel were examined. USR created a nanostructured surface layer approximately 15 µm deep, increasing hardness by 61% (from 177 HV to 290 HV). Wear tests demonstrated significantly lower mass loss for USR-treated samples, especially at higher speeds, due to the surface layer's high hardness, which reduced abrasive and adhesive wear. USR effectively enhances the mechanical and wear properties of 316L stainless steel, particularly in lubricated environments [Wang 2019].

The implications of heat treatment on the wear resistance of Fe-W coatings produced by the method of electrodeposition were investigated. These coatings are prepared with 24 at. % tungsten, and the effect of heat treatments at the temperatures up to 800°C has been investigated. Fe2W and FeWO4 phases, formed after annealing at 800°C, revealed better wear resistance and reduced tribo-oxidation than that of the as-deposited sample and lower-temperature coated samples. When the Fe-W coating was annealed at 800 centigrade the value of the coefficient of friction (~0.8) and the wear rate comparable to hard chromium coatings reveal the possible use of the Fe-W coating as a protective and sustainable coating [Mulone 2019].

The wear and friction behaviour of stainless steel 420 against 100Cr6 balls under dry, minimum quantity lubrication (MQL), and pool conditions revealed that MQL and pool conditions significantly improved the tribological properties of stainless steel 420. Pool lubrication provided the lowest volume loss, wear depth, and friction coefficient, followed by MQL, with dry conditions showing the highest values. Pool lubrication effectively enhances wear resistance and reduces friction in stainless steel 420 [Gupta 2023].

Cobalt plating on UNS430 stainless steel was studied for high-temperature fuel cell interconnect applications. The cobalt coating, applied via electroplating and oxidized at 800°C, formed mixed spinel phases that improved oxidation resistance and electrical conductivity. The cobalt-coated samples maintained a low area-specific resistance (ASR) of 0.026 $\Omega \cdot cm^2$ after 1900 hours of oxidation, whereas uncoated samples developed thick, porous oxides with significantly higher ASR. The cobalt coating enhances the stability and conductivity of stainless steel, making it suitable for high-temperature applications [Deng 2006].

Properties both mechanically and corrosion were improved for the Co-Ni-Fe alloy coatings deposited on stainless steel. Stainless steel is namely subjected to the greatest rise of its hardness and corrosion resistance after coating. [Guo 2022].

X-ray diffraction (XRD) method proved that the as-deposited Co-Ni-Fe coatings possessed a single-phase face centred cubic (FCC) structure. Consequently, both Ni-Mo and TiC/TiB2 coatings contained a ceramic phase which improved their mechanical performance. FESEM study of Co-Ni-Fe coatings showed homogeneous distribution of nanocrystalline grains involving enhanced corrosion and wear resistance. Co-Ni-Fe coatings had increased wear resistance at longer deposition times and coatings containing TiC/TiB2 had high wear resistance due to the ceramic nature of the components. The corrosion resistance of Ni-Co-Fe coatings was also higher compared to pure metals [Wardan 2021] [Sun 2013].

Previous investigations of Co-Fe electrodeposition exist although research about the influence of Co-Fe ratio changes on 316 stainless steel wear and corrosion properties remains scarce. Co-Fe electrodeposition will undergo systematic investigation while optimizing parameters for performance improvement. Characterization of the coatings at different Co-Fe ratios of 50: This work aimed at identifying the ratio of 50%sacrificial, 75%:25%, and 95%:5% that will achieve the right balance of mechanical resistance to corrosion and protection for use in harsh environments.

The Co-Fe electrodeposited coatings in optimized form from this research aim for aerospace applications on turbine blades and landing gear and actuator units since they require superior wear resistance and corrosion resistance. Since these parts are used extensively where considerable mechanical loads are to be supported as well as subjected to such severe corrosive environments, consequently, wear and corrosion resistance assumes paramount importance. While sustaining the application of the CV technique in correct deposition, the study aims to create wear-resistant coatings for prolonged aviation service to reduce recurrent costs of repair and prolong the useful lives of aerospace components, inter alia.

This work identifies novelty as it utilizes cyclic voltammetry (CV) method of an electrochemical workstation to optimize Co-Fe electrodeposited coatings. This method allows precise control over deposition parameters, ensuring uniform coatings with varied Co-Fe ratios (50:50, 75:25, and 95:5). The initial general qualitative analysis through the use of XRD, EIS and FESEM that characterizes cobalt-iron coating in this research aims to reveal the reactivity of cobalt and iron especially in forming a uniform, continuous and fully BCC structure coating to meet the demand of wear and corrosion requirements of severe industrial applications.

2 MATERIALS AND METHOD

The Co-Fe standard material received electrodeposition treatment for AISI 316 stainless steels. AISI 316 proved best for this application because it shows superior corrosion resistance together with high mechanical strength and excellent thermal stability suitable for aerospace and marine use. Additionally, its widespread industrial use ensures the relevance of this study for real-world applications. The size of the specimen obtained was about 25 mm x 25 mm x 4 mm from a stainless steel plate. Emery papers of 400, 600, and 1200 grit were used in polishing the substrates and further mirror polished using the cloth polishing wheel machine. Clean with sulfuric acid followed by acetone and then rinsed in distilled water. A solution for electrodeposition utilized cobalt sulfate ($CoSO_4$) together with iron sulfate ($FeSO_4$) citric acid ($C_6H_8O_7$) and sodium sulfate (Na_2SO_4). The table 1 presents the chemical compositions of electrodeposition solutions containing different Co-Fe ratios (50:50, 75:25, and 95:5). All mass values were measured with a precision of ±0.01 g, ensuring consistent solution composition across different Co-Fe ratios. Prior to electrodeposition all salts underwent homogenous dissolution process through deionized water stirring at a constant rate. After being stirred with magnets at 500 rpm for one hour the solution received additional fragmentation through sonication to prevent the formation of agglomerates. The solution's acidity needed monitoring through a pH meter for maintaining steady deposition quality. After mixing the components the solutions aged under controlled temperature of 24°C for 48 hours to enable chemical property stabilization. The solution turned into a deep reddish color during this time which confirmed the success of cobalt and iron salts incorporation. The tests results showed that electrolyte stability exceeded three months without signs of breakdown. A three-electrode configuration became the basis for the electrodeposition operation.

- Working electrode: 316 stainless steel substrate

- Reference electrode: Ag/AgCl
- Counter electrode: Platinum

Deposition was carried out using the cyclic voltammetry (CV) method in galvanostatic mode, maintaining a potential range of -0.5 V to 0.5 V with a scan rate of 0.1 mV/s. The deposition current density was set at 10 mA/cm², with a constant deposition time of 30 minutes for all Co-Fe ratios. The electrolyte bath was agitated at 100 rpm using a recirculating system to maintain uniform ion distribution. After deposition, the coated substrates were rinsed with deionized water and dried under controlled conditions.

Such an arrangement allowed tight control over the electrochemical conditions and conditions that permitted uniform deposition of cobalt and iron onto 316 stainless steel substrates.

Compound	Mass (g)		
	50:50	75:25	95:05
$CoSO_4$	5	7.5	9.5
$FeSO_4$	2.5	1.25	0.25
$C_6H_8O_7$	7.5	7.5	7.5
Na_2SO_4	5	5	5

Table 1. Formulation of Electrolyte for Co-Fe Deposits

A stylus profilometer was used to measure the thickness of Co-Fe coatings with different ratios of Co and Fe deposited on 316 stainless-steel. The results were evidence of disparities in the thickness of the coating based on the chemical makeup of the Co-Fe alloy. The 50: From the above and below the 50 Co-Fe ratio gave the highest coating thickness of 35 µm, showing a thicker deposition layer. The 95: The Co–Fe ratio of 5 produced a coating thickness of 15 µm while the lowest Co-Fe ratio 75:25 for the thinnest coating at 3 µm. These differences in thickness are important as they are defined by the wear-fighting capability and durability of the coatings where higher thickness is preferable for affording higher levels of corrosion and mechanical protection.

3 COATING CHARACTERIZATION

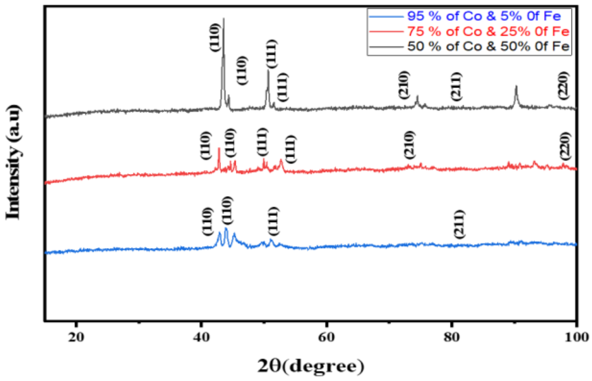
This study utilized X-ray diffraction (XRD) analysis, field emission scanning electron microscopy (FESEM), and energy dispersive X-ray (EDX) to examine the impact of Co-Fe alloy coating on the surface of 316 stainless steel at various ratios, including 50:50, 75:25, and 95:05. The samples were measured using a Cu-Kα1 (1.5405 Å) source and a scan rate of 40 min^-1 for the 29 range of 0° to 120°. The samples were characterized for morphology using the ZEISS SIGMA 300 FESEM with the micrograph prepared at electron beam energy of 10 keV.

The Linear Reciprocating Test Rig tribometer performed the wear-resistant evaluation through controlled sliding tests. During the test execution researchers utilized a counterbody consisting of a 6 mm diameter 316 stainless steel (SS) ball. The experiment used 1N normal force to study a 3mm reciprocal motion sample which operated at 2Hz frequency. The experimental period lasted thirty minutes under RT temperature conditions with 38% relative humidity. During testing the conditions consisted of 50°C as the operating temperature. A standardized evaluation of the sample's wear resistance occurs through these essential experimental parameters.

The Potentiodynamic Polarization (PDP) test was conducted using Octosat5000 equipment in a view to analyze the corrosion characteristics of the electrodeposited coatings on the zinc substrate. Performed at room temperature in 3.5% NaCl, the PDP test evaluated corrosion parameters in the Tafel potential range using cathodic and anodic polarization potential against density characteristics. The corrosion resistance of the coatings was also measured using Electrochemical Impedance Spectroscopy (EIS) to obtain impedance values, which was helpful in studying the electrochemical behaviour and efficiency of the coatings applied on the 316 stainless steels.

Figure 1. XRD pattern of Co-Fe coating on 316 Stainless-steels

4 RESULTS AND DISCUSSION



4.1 *X-ray diffraction analysis*

The X-ray diffraction (XRD) analysis of the Co-Fe ratios (50:50, 75:25, and 95:05) compared with the JCPDS reference data No. 44-1433 reveals consistent crystalline structures characterized by peaks at 2θ values of 44.83° (110), 55.83° (111), 74.37° (210), 82.91° (211), and 99.32° (220). Co-Fe 50:50 ratio has peaks at prominent (110), (111), and (211) locations with good alignment to JCPDS standards with a bcc phase (Figure 1). Peaks for Co-Fe 75:25 ratios also follow similar variation, thus showing a structure of bcc with very minor difference in the compound. The Co-Fe 95:05 ratios maintain the main bcc peaks while presenting additional peaks, suggesting structural changes due to higher Co content. Overall, the Co-Fe ratios exhibit phase structures consistent with JCPDS No. 44-1433, demonstrating bcc phases and crystallographic variations influenced by composition. Its specific arrangement of atoms gives atomic structure a Body-Centered Cubic (BCC) structure in Co-Fe coatings on 316 stainless steels, which enhances strength and wear resistance. Coatings with BCC structural formation occur when iron contents are above 20% of the total composition and also allow for the control over deposition parameters to tailor its characteristics to the desired application requirements. Corrosion resistivity is improved by passivating a stable layer promoting the formation of a very compact oxide film. At sub 100 nm, the grain structures created by monocrystalline grains or with inclusions of hard particles increase wear resistance without a reduction of corrosion protection. Due to synergistic properties between Co and Fe, such coatings combine the properties of high strength mechanical performance with superior corrosion resistance. Therefore, such coatings can be used also in corrosive environments that require simultaneous corrosion and wear protection.

4.2 *Morphology and microstructure*

The FESEM microstructures and EDX analysis of 316 stainless steels coated with varying Co-Fe ratios (50:50, 75:25, and 95:5) reveal distinct differences in their morphology and composition. These analyses are crucial for understanding the structural properties and elemental distributions within the coatings, which play a significant role in their overall performance. The variations in these ratios provide insights into how different compositions affect the coating's structural integrity and homogeneity.

The 50:50 Co-Fe ratio exhibits a homogenous distribution of particles and a compact surface morphology, as shown in Figure 2(a). This blend makes for good bonding and gives a proportionate property profile of the resulting adhesive. Because Co and Fe particles are uniformly distributed, the coating obtain has proper structural integrity, which leads to stability. The EDX analysis in Figure 2(d) shows the present of both elements in equal percentage signifying successful deposition. This uniformity enables the material to offer consistent performance and reliability in numerous applications, which makes the composition advantageous for numerous uses.

The microstructure of the 75:25 Co-Fe ratio, as presented in the figure 2(b), exhibits a denser and smoother surface as compared with the 50:50 ratio. It is found that there are fewer surface defects because Co has a higher concentration compared with other elements, and this may be useful in applications that require less surface roughness. Nevertheless, the EDX analysis shows that the ratio of element intensity is slightly shifted towards Co, which can influence the uniformly of the coating. While the increased Co content contributes to a denser microstructure, it may not provide the same level of structural integrity as with 50:50 ratio coated substrate. This ratio provides a balance between smoothness and mechanical soundness for systems whereby moderate structural heft is wanted.

The 95:5 Co-Fe ratio owns the finest average particle size and highest relative density supported by Image 2(c). As Co predominates, there is a very dense, dense layer that has few porosities and other surface flaws. With a view to the EDX analysis, this composition is highly biasing in the favor of Co and produces a huge on the properties of coatings. According to the dense microstructure, this ratio may be highly beneficial in the application where compact and solid coating characteristic is served. However, it might be seen that the content of Fe is very low that can also affect the flexibility and the mechanical property on the coating especially on the dynamic coating applications. The high contents of Co can cause the brittleness of the coating which does not easily smoothen its form to adapt to stress and deformation.

The FESEM and EDX analyses highlight the importance of optimizing the Co-Fe ratio for coating 316 stainless steel. The 50:50 Co-Fe ratio emerges as the optimal choice, providing a balanced and uniform coating with excellent structural properties. This ratio ensures a homogenous distribution of particles, resulting in a coating that can maintain stability and reliability in various applications. The 75:25 and 95:5 ratios, while offering certain advantages, do not achieve the same level of performance as the 50:50 ratio. These findings underscore the significance of precise composition control in developing effective coatings for stainless steel applications.

The 50:50 Co-Fe ratio indicates good adhesion with uniform and homogenous microstructure in the BCC structure that is stronger and flexible but is strongly bonded with the substrate. For the 75:25 ratio, there is moderate adhesion but slight brittleness since the content of cobalt is high and still possesses a BCC structure, but this leads to the decrease of uniformity. The lowest adhesion and the highest brittleness ratio with a 95:5 ratio and dense microstructure and cobalt-dominated BCC phases is liable to crack under stress.

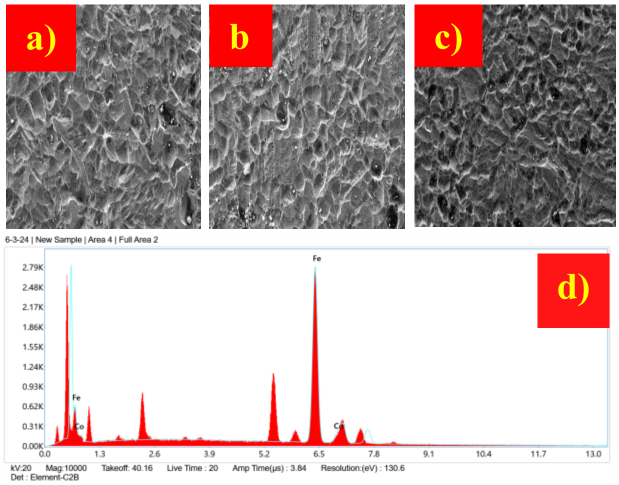


Figure 2. Coated 316 stainless-steels FESEM microstructure at 500 X magnification (a) 50% of Co &50% of Fe b) 75% of Co & 25% of Fe c) 95% of Co & 5 % of Fe d) EDX

4.3 *Friction and Wear Analysis*

Table 2 and Figure 3 show the comparative investigation of 316 Stainless Steels. The best wear performance was made by 50:50 co-Fe ratio having minimum coefficient of friction at 0.29 with longest time wearing of 1082 secs, it suggests a wear resistance capability. Similarly, in Figure 4, literature results for Coating C (50% ceramic content) reveal the minimum COF at 0.314 ± 0.005 and the least wear width at 645 µm, which once again confirms the maximum wear resistance [Liu 2023]. In this case also, the balanced material distribution of both the cases resulted in superior tribological properties. For the 75:25 ratio, my test had a somewhat higher COF of 0.31 and a shorter wear time of 669 s, making it the worst composition. From the literature, Coating B at 30% ceramic has a COF of 0.343 ± 0.005 with medium wear resistance as compared to Coating C. This shows that deviating from the best composition yields the worst performance. Although the 95:05 ratio of my study had the highest COF value of 0.33, it had better wear resistance than the 75:25 ratio, which had a wear time of 754 seconds, thus showing some structural advantages. In both literatures, Coating D with 70% ceramic content had a COF of 0.403 ± 0.006, and it could be inferred that higher content of ceramic caused particle agglomeration, leading to decreased performance. Thus, the experimental results confirm that the compositions like 50:50 Co-Fe ratios are optimal to get low friction and high wear resistance. This alignment puts robustness in your findings and shows its relevance to similar tribological systems.

The wear track analysis of Co-Fe coatings on 316 stainless steels, as shown in Figure 5(a), 5(b), and 5(c), highlights the impact of cobalt content on wear resistance. Figure (a) (50% Co & 50% Fe) displays the smoothest surface with minimal wear tracks, demonstrating superior wear resistance due to balanced mechanical properties. Figure (b) (75% Co & 25% Fe) shows deeper wear tracks, indicating reduced abrasion resistance. Figure (c) (95% Co & 5% Fe) exhibits the most pronounced wear tracks, reflecting significant wear due to brittleness. Thus, the 50% Co & 50% Fe composition offers optimal performance by balancing hardness and durability.

Co-Fe Ratios	Time (s) ± SD	COF ± SD
50:50	1082 ± 15	0.29 ± 0.01
75:25	669 ± 12	0.31 ± 0.02
95:05	754 ± 18	0.33 ± 0.01

Table 2. Co-Fe Ratios: Wear and Tribological Performance

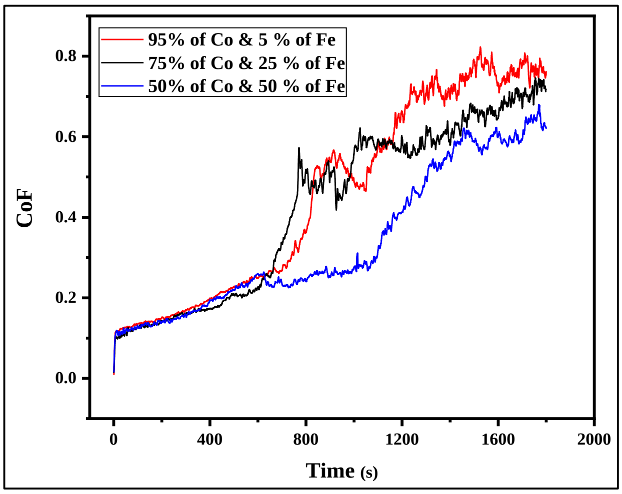


Figure 3. Recorded friction curves for Co-Fe on 316 Stainless-Steel with different ratios

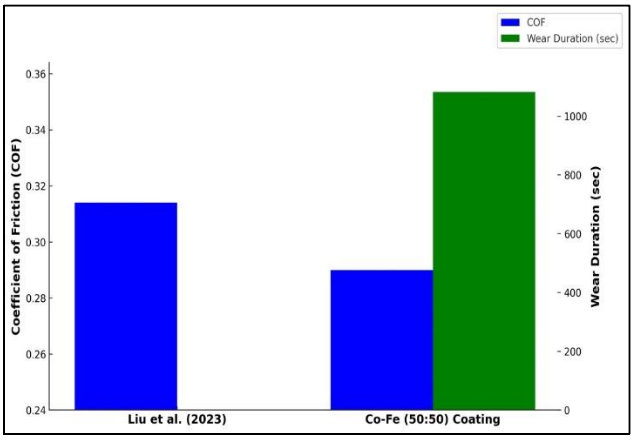


Figure 4. Comparison of Wear Resistance: Coefficient of Friction & Wear Duration

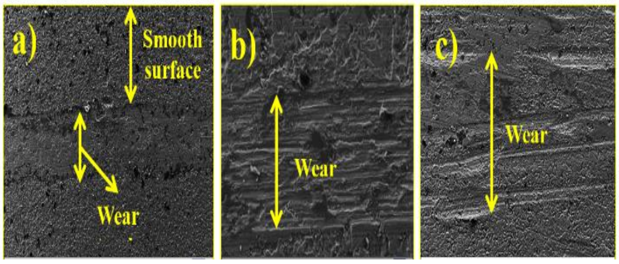


Figure 5. Coated 316 stainless-steel microstructure as shown by FESEM after wear (a) 50% of Co &50% of Fe (50X magnification) (b) 75% of Co & 25% of Fe (200X magnification) (c) 95% of Co & 5 % of Fe (100X magnification)

4.4 *Corrosion Behaviour*

The electrochemical corrosion behavior of 316 stainless steels with various Co-Fe ratios was studied by the tafel extrapolation and EIS methods. The experimental setup is described below: a working electrode of 316 stainless steel, Ag/AgCl reference electrode, and platinum counter electrode in a 3.5% NaCl solution. For PDP, the voltage range was swept from -0.5V to +1.5V relative to the open circuit potential with a scan rate of 0.5 mV/s. The frequency range covered by EIS measurements ranges between 0.01 Hz and 100 kHz with an AC voltage of 5-10mV. Figure 6 Tafel plot analysis and table 3 Corrosion rate data Overall electrochemical behavior of Co-Fe coatings on 316 stainless steel. The highest results were obtained by using the 50:50 Co-Fe ratio which gave the lowest corrosion current density of Icorr = 12.752 µA, and corrosion rate of 0.0037 mm/year. With Ecorr at -259.534 mV, it has very high negative corrosion potential and, thus is a very active protective system; the anodic slope (βa = 921.1 mV) indicated strong passive layer formation enhancing its corrosion resistance. On the other hand, ratios 75:25 and 95:5 Co-Fe indicated higher corrosion current density and rates, meaning that these are not effective protective systems.

The uncoated 316 stainless steel, with a moderate degree of corrosion resistance (Ecorr = -228.806 mV, Icorr = 11.132 µA, and a corrosion rate = 0.0115 mm/year), did not exhibit enhanced protection properties as found for the optimized Co-Fe coatings. Specifically, the 95:5 ratio exhibited the worst performance of all tested coatings with the highest corrosion rate of 0.0214 mm/year and Icorr of 20.971 µA, probably due to its imbalanced composition and weaker formation of a passive layer. These results therefore show that the best coating composition is the 50:50 Co-Fe ratio, showing better corrosion resistance and electrochemical stability.

Figure 7, Nyquist plot figure gives a wide-ranging view of the electrochemical impedance behavior of Co-Fe electrodeposited coatings on 316 stainless steels at various compositional ratios (50:50, 75:25, and 95:5) compared to uncoated stainless steel. The 50:50 Co-Fe coating has the largest semicircle; hence it has the highest impedance among the tested samples. The long semicircle displays higher resistance to corrosion for the BCC uniform microstructure that forms and effectively minimizes the diffusion of ions and the penetration of the electrolyte. In the 75:25 and 95:5 Co-Fe ratios, the semicircles are more diminutive but have lower charge transfer resistances and hence corrosion protection. The smallest semicircle was found in the 95:5 ratio, which indicated no uniform coating and poor barrier performance. The low impedance of the uncoated 316 stainless steel suggests a more susceptible nature to corrosion.

Table 3. Results of Corrosion Resistance on 316 Stainless-Steel with Co-Fe Coatings

Co-Fe Ratio	E_{corr} (mV)	I_{corr} (µA)	β_c (mV)	β_a (mV)	Rate of Corrosion mm/year
50-50	-259.534	12.752	124.0	921.1	0.0037
75-25	-228.267	3.587	100.8	356.4	0.0131
95-05	-240.391	20.971	173.9	161.0	0.0214
316 stainless steels	-228.806	11.132	84.3	325.6	0.0115

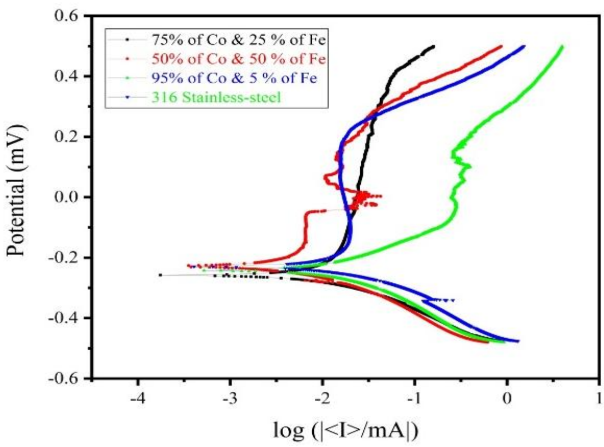


Figure 6. Different Co-Fe Ratios and Potentiodynamic Polarization Curves on 316 Stainless-Steel

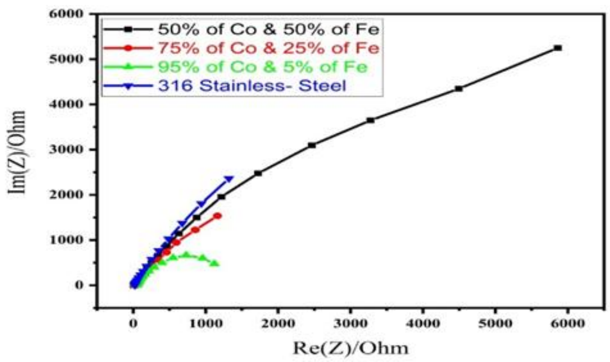


Figure 7. Rate of Corrosion of Various Co-Fe Ratios on 316 Stainless-Steel

5 CONCLUSIONS

1. When Co-Fe established a 50-50 ratio it achieved optimal results by producing a uniform and defect-free 35 µm thick coating with body-centered cubic (BCC) microstructure formation.

2. Tribological tests indicated that 50:50 Co-Fe coating reached 1082 seconds as the highest duration with 0.29 as the lowest coefficient of friction thus ensuring its position as the most wear-resistant solution among these ratios.

3. Tests confirmed the 50:50 Co-Fe mixture had the best corrosion resistance by maintaining a low annual corrosion rate of 0.0037 mm/year together with small corrosion current density (Icorr = 12.752 µA) and very negative corrosion potential (-259.534 mV).

4. Analysis through FESEM and EDX showed that a 50:50 Co-Fe ratio led to consistent microstructural organization which increased both mechanical stability and service life.

5. Nyquist plot results showed that the 50:50 Co-Fe coating formed the most stable passive layer together with the maximum impedance value which indicated extended corrosion resistance duration.

6. Research findings prove that optimized Co-Fe electrodeposits obtained through cyclic voltammetry become suitable for aerospace components including turbine blades and landing gears and actuator units that require intense anti-corrosion properties.

7. The paper presents a novel scientific approach to use cyclic voltammetry for controlling electrodeposited coating composition which opens possibilities for protective materials development.

Future research must focus on extending the long-term stability of Co-Fe coatings through high-temperature-resistant and corrosive tests particularly for aerospace and marine industries. Further enhancement of wear and corrosion resistance can be achieved through evaluations of both post-deposition heat treatments and composite coating formats incorporating Co-Fe with ceramic components. The development of eco-friendly deposition methods combined with alternative coating techniques will enhance both sustainability and cost-effectiveness of the process.

FUNDING

This article was co-funded by the European Union under the REFRESH – Research Excellence For REgion Sustainability and High-tech Industries project number CZ.10.03.01/00/22_003/0000048 via the Operational Programme Just Transition and has been done in connection with project Students Grant Competition SP2025/062 „Specific research on progressive and sustainable production technologies" financed by the Ministry of Education, Youth and Sports and Faculty of Mechanical Engineering VŠB-TUO

REFERENCES

[Adull Manan 2017] Adull Manan, N.F., Nik Mohd Masdek, N.R., Abdul Aziz, Q., & Salleh, Z. (2017). The study of corrosion behaviour of cobalt-iron (CoFe) alloy coating. Journal of Mechanical Engineering (JMechE), vol. 4, pp. 167–183.

[Deng 2006] Deng, X., Wei, P., Bateni, M.R., & Petric, A. (2006). Cobalt plating of high temperature stainless steel interconnects. Journal of Power Sources, vol. 160, no. 2, pp. 1225–1229.

[Guo 2022] Guo, J., & Yao, X. (2022). Preparation of Ni-Co-Fe alloy coating on copper by ultrasound-assisted electrodeposition and its mechanical property. International Journal of Electrochemical Science, vol. 17, no. 7, 220740.

[Gupta 2023] Gupta, M.K., Demirsöz, R., Korkmaz, M.E., & Ross, N.S. (2023). Wear and friction mechanism of stainless steel 420 under various lubrication conditions: a tribological assessment with ball on flat test. Journal of Tribology, vol. 145, no. 4, 041703.

[Jin 2013] Jin, X., Wang, B., Xue, W., Du, J., Wu, X., & Wu, J. (2013). Characterization of wear-resistant coatings on 304 stainless steel fabricated by cathodic plasma electrolytic oxidation. Surface and Coatings Technology, vol. 236, pp. 22–28.

[Liu 2010] Liu, L., Li, Y., & Wang, F. (2010). Electrochemical corrosion behavior of nanocrystalline materials—a review. Journal of Materials Science & Technology, vol. 26, no. 1, pp. 1–14.

[Mulone 2019] Mulone, A., Nicolenco, A., Imaz, N., Martinez-Nogues, V., Tsyntsaru, N., Cesiulis, H., et al. (2019). Improvement in the wear resistance under dry friction of electrodeposited Fe-W coatings through heat treatments. Coatings, vol. 9, no. 2, 66.

[Roseley 2022] Nik Roseley, N.R., Hyie, K.M., Nik Masdek, N.R., 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, vol. 34, pp. 56–68.

[Sun 2013] Sun, Y. (2013). Sliding wear behaviour of surface mechanical attrition treated AISI 304 stainless steel. Tribology International, vol. 57, pp. 67–75.

[Wang 2019] Wang, C., Han, J., Zhao, J., Song, Y., Man, J., Zhu, H., et al. (2019). Enhanced wear resistance of 316 L stainless steel with a nanostructured surface layer prepared by ultrasonic surface rolling. Coatings, vol. 9, no. 4, 276.

[Wardan 2021] Wardan, R., Shamsudin, S.R., Sampasivam, T., Wahid, M.F.M., & Yati, M.S.D. (2021). Effects of different pH of 3.5% NaCl solution on steel under zero charge corrosion protection technique. Journal of Physics: Conference Series, vol. 2080, no. 1, 012021.

CONTACTS:

S.P. Samal, Department of Biosciences, Saveetha School of Engineering,
Saveetha Institute of Medical and Technical Sciences, Chennai 602105, India.
spsamal24@gmail.com