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ENHANCING EFFICIENCY AND LONGEVITY OF COLD ROLLING PROCESS THROUGH HARD-CHROME COATINGS: A COMPARATIVE STUDY

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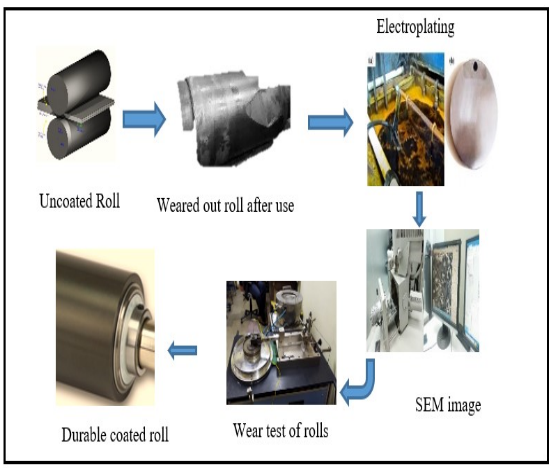
Graphical abstract



Abstract

Efficiency in rolling processes relies heavily on the durability of rolls, a critical tool in the operation. However, dynamic rolling under high loads often results in frequent roll wear, leading to reduced productivity, efficiency, and substantial capital losses. This study investigates the application of zinc and hard chrome coatings to the EN19 substrate in cold rolling process, verified through Energy Dispersive X-ray Spectroscopy (EDS) and X-ray Diffraction (XRD) analyses. Experimental tests on a pin-on-disk wear machine reveal mass wear rates: Hard chrome, Zinc, and EN19 at 1.67 x 10^-07, 3.33 x 10^-07, and 25.33 x 10^-07 (gm/Nm) respectively. Hard chrome exhibits superior performance, lasting 15.19 times longer than EN19 and twice as long as zinc. Zinc extends EN19's life by 7.6 times. Scanning Electron Microscopy (SEM) images show adhesive and abrasive wear as the primary causes of roll wear. Hard chrome coating stands out as an effective solution to significantly extend roll life, minimizing capital and time losses associated with roll wear. Additionally, hard chrome offers low friction and excellent corrosion resistance, making it a promising choice for enhancing cold rolling process efficiency and cost-effectiveness.

Keywords: Sliding wear, Cold Rolls, Zinc, EN19, Hard Chrome.

1.0 INTRODUCTION

Rolling is a vital industrial process employed in the production of various materials, including sheets, I-channels, bars, and strips. It involves the reduction of work-piece thickness while increasing its length by applying compressive forces using rolls. However, the harsh loading conditions in rolling processes lead to significant wear and tear of the rolls [1]. Modern steel plants rely on automated production lines, where uncoated rolls have a limited lifespan of approximately 2-3 months. After this period, regrinding becomes necessary, but this practice reduces the roll's dimensions, making it impractical beyond a certain point. Replacing rolls disrupts production lines, resulting in increased overall production costs. Consequently, there is a critical need to extend the lifespan of rolls to enhance the efficiency and cost-effectiveness of rolling processes. Various types of coatings and electroplating processes are employed for a wide range of applications, including aesthetics, functionality, and industrial purposes. These processes serve to provide protection against wear, corrosion, and high-temperature oxidation while simultaneously enhancing chemical resistance and lubricity [2]–[4]. Various coatings, including Nickel, Chromium, Cobalt, Phosphorus, and more, find extensive use across diverse industrial applications. These coatings aim to achieve ideal surface conditions, thereby enhancing the material's resistance to wear, erosion, abrasion, and other forms of deterioration due to their high hardness [5]. It was found that at room temperature, the wear characteristics of hard chromium and electroless nickel-phosphorus coatings were similar. However, hard chromium performed better on rough surfaces, while electroless nickel-phosphorus excelled on smooth surfaces. Importantly, the substrate's load-bearing capacity significantly influenced the performance of the coatings [6]. Regardless of the composition and structure of the zinc coatings, they all form a thin zinc oxide film upon deposition, providing additional protection to steel components against environmental factors [7]. Zinc deposition significantly enhanced the corrosion resistance of mild steel [8]. The speed at which wire is drawn has a substantial impact on the thickness, morphology, and corrosion resistance of the zinc coating applied to the wire surface [9]. In comparison to WC specimens, the fatigue strength of the standard steel AISI 4340 substrate decreased to a greater extent when subjected to chrome electroplating. In terms of wear weight loss tests, the performance of WC coating surpassed that of chrome electroplating [10]. When compared to uncoated pins, those that underwent hard chrome plating exhibited reduced material transfer, lower friction, and a decreased generation of iron fines. These reductions can be attributed to the unique tribo-chemical properties of the chromium layer [11]. The HDG (Hot-dipped galvanized) fared better than the TZD (Thermal zinc diffusion) in the U-bend specimens, however this is thought to be due to the higher w/c and lower cover, which allowed chloride in too quickly, preventing the TZD specimen from effectively forming a protective passive coating [14]. A steel rod's lifespan gets shorter because of rust, high heat, and wearing down when we use it for different tasks. To make it last longer, one can put a layer of hard chrome on it. But this chrome layer becomes less hard as it goes deeper below the surface. So, the deeper it goes, the less protection it offers [15]. The results reveal that zinc coating reduces the yield strength of the steel plate but has no discernible effect on the hardening index [16]. The influence of the substrate, particularly for outside use, is a recurring issue. Zinc coatings on inert substrates typically outlast coatings on many common building materials such as wood, stone, or metal [17]. Zinc coatings have various qualities that are determined by the composition, microstructure, and morphology of the overlay that forms the majority of the coating [18].

1.1 Novelty of This Study

After reviewing existing research, it's evident that zinc and hard chrome coatings have proven effective in various applications. However, there's limited prior research on using these coatings to extend the lifespan of EN19 rollers in cold rolling process in the heavy steel industry. Therefore, this study aims to enhance roller durability in heavy steel industry applications by applying zinc and hard chrome coatings to the EN19 base material. Ultimately, the goal is to boost rolling process productivity. Sliding wear tests are employed to determine the wear of the coating however, for replicating the wear mechanism in cold rolling mill rolls, the reciprocating sliding tests were recommended [12].

2.0 METHODOLOGY

The selection of coating materials was based on their physical and chemical properties, as determined through a comprehensive literature review. The application of Hard Chrome was achieved using the Electro Deposition Coating (EDM) method, commonly referred to as the E-coating method [19-20]. This procedure closely resembles electroplating. Coating materials were chosen based on their physical and chemical properties identified through a literature review. The process commences with thorough surface cleaning, which may involve methods such as ultrasonic washing, degreasing, de-rusting, or manual cleaning. This step ensures a clean substrate surface. After cleaning, the surface undergoes water rinsing to eliminate any residual chemicals from the cleaning process.

To facilitate chrome plating, the substrate's surface is activated using chrome salt. This activation process adjusts the substrate's nature to be receptive to chrome plating. With the surface now activated, the substrate is prepared for chrome plating. It is connected to the cathode, a negatively charged component, while chromium is attached to the anode, which carries a positive charge. When an electric current is supplied, the solution transforms into ions: chromium ions become positively charged, and the substrate becomes negatively charged. Consequently, chromium ions are attracted to the negatively charged substrate, resulting in the deposition of chromium onto the substrate's surface. Chromic acid or chrome sulfate is commonly used as a plating solution. Following the completion of the Hard Chrome plating process, a thorough water rinse is performed to remove any residual substances. The coated substrate undergoes a final inspection to ensure the quality and integrity of the Hard Chrome coating. Surface roughness measurements for both the substrate and coatings were conducted using the TR200 Surface Roughness Tester. The chemical composition analysis of the coatings was obtained through the Energy Dispersive X-ray Spectroscopy (EDS) process.

For tribological property evaluation, a dry wear test was carried out. The test specimens were prepared using EN19 cylindrical substrates with a diameter of 40 mm and a thickness of 6 mm, as specified in Table 1. The substrates underwent grinding as part of the preparation process. One of these substrates was subjected to a 100-micron thick Hard chrome coating applied via the Electro Deposition Coating Method, as previously described. In parallel, another substrate received a 100-micron thick Zinc coating using the same Electro Deposition Coating Method. The dry wear tests were performed using a Pin-on-Disk wear test machine from DUCOM, Bangalore, India. In this machine, a specific load is applied, and the track diameter is configured to be generated on the specimen through material removal. The rotational velocity in RPM is also set for the disc upon which the substrate is mounted. When the machine is activated, the disc rotates at the predetermined RPM, causing the specimen to move in a circular motion. At this point, a hard Silicon Nitride (Si_3N_4) ball, with an 8 mm diameter, is affixed to a lever. This ball comes into contact with the specimen, rubbing and scratching it in an attempt to remove the coating material within the defined track diameter. As a result, a circular track is created on the specimen's surface, which becomes visible, as illustrated in Figure 1.

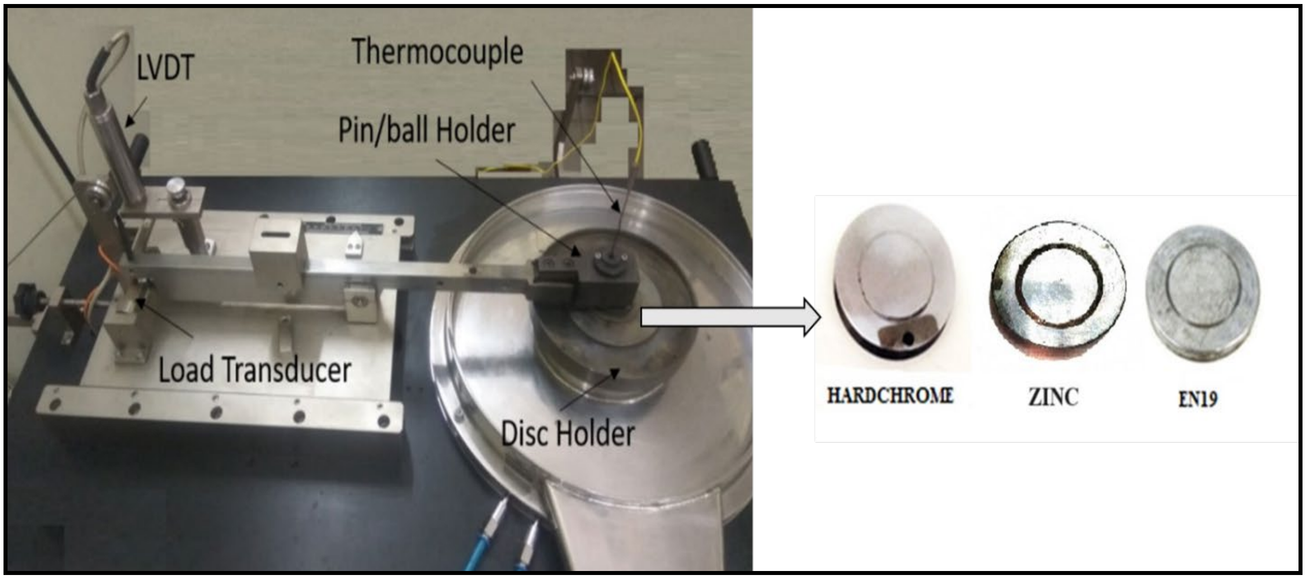


Figure 1 Track formed on specimen machine after wear test using Pin-on-Disk wear test Tribometer machine.

The weight of the specimen is measured both before and after the wear test using a High Precision Laboratory Balance manufactured by Contech Instruments Ltd. The change (difference) in weight is determined by subtracting the final weight after the wear test from the initial weight of the specimen before the wear test. Subsequently, the Mass wear rate is calculated using the following formula:

Mass wear rate (gm/Nm) = Change in weight (gm) / [Load (N) x Sliding distance (m)]

This formula quantifies the rate at which material is worn away during the test, expressed in grams per Newton-meter (gm/Nm).

Table 1 Summary of Wear Test Parameters

Material	**EN19 (Substrate), Hard chrome, Zinc Coating**
Specimen Dimensions	Diameter: 40 mm, Thickness: 6 mm
Surface Finish	0.25 to 0.7 µm for Hard chrome, Zinc, EN19
Hardness	- Hard chrome: 55 HRC
	- Zinc: 45 HRC
	- EN19: 23 HRC
Testing Conditions	Sliding Velocity (V): 1 m/s
	Normal Load (P): 30 N
	Sliding Distance: 500 m
	Track Diameter: 30 mm
	RPM: 637

X-ray diffraction (XRD) analysis was conducted using a D8 DISCOVER machine manufactured by Bruker. The XRD measurements were carried out with the following parameters: a voltage of 40 kV, a current of 40 mA, and a power output of 1600W, utilizing a copper tube with a wavelength of 1.5418 Å. Subsequently, the XRD graphs were generated using Origin software, based on the data acquired from the XRD machine for various specimen coatings. Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive Spectroscopy (EDS) analyses were conducted on the EN19 substrate using a Quanta 200F machine manufactured in the Netherlands. Additionally, FESEM and EDS analyses were carried out for the Hard chrome and Zinc coatings using a ZEISS Gemini SEM 300 model machine. EDS, or Energy Dispersive Spectroscopy, was applied to various samples using the same ZEISS machine for comprehensive material composition analysis.

3.0 RESULTS AND DISCUSSION

Adhesion Strength Test result (as per ASTM C633-2017) was found to be 12580 psh for Hardchrome and 9750 psh for Zinc. Five readings were taken for surface roughness and hardness and were averaged out. The surface roughness and hardness of Hard chrome, Zinc, and the EN19 substrate, have measured 0.576, 0.249, and 0.722 Ra microns, and 55 HRC, 45 HRC, and 23 HRC, respectively. Wear test results revealed that the coefficient of friction (COF) for Hard chrome, Zinc, and EN19 were 0.554, 0.576, and 0.66, respectively as shown in figure 2(a). Additionally, the mass wear rate was calculated, with three readings taken for each material at 30 N load. The average values yielded mass wear rates of 1.66667 x 10^-07 gm/Nm for Hard chrome, 2.66667 x 10^-07 gm/Nm for Zinc, and 2.53333 x 10^-06 gm/Nm for EN19 are shown in figure 2(b). These findings indicate that the EN19 substrate exhibited the highest wear rate, followed by Zinc, while Hard chrome emerged as the most effective coating, demonstrating the least wear among the materials tested.

Table 2 Wear Test Experimental Results

Material	Load (N)	V (m/s)	Sliding Distance (m)	Speed (rpm)	Track Diameter (mm)	Disc Weight Before (gm)	Disc Weight After (gm)	Change in Weight (gm)	Mass Wear Rate (gm/Nm)	COF
Hard Chrome	30	1	500	637	30	64.349	64.3465	0.0025	1.666 x 10^-07	0.554
Zinc	30	1	500	637	30	65.718	65.713	0.005	3.333 x 10^-07	0.576
EN19	30	1	500	637	30	65.502	65.464	0.038	2.533 x 10^-06	0.66

Table 2 presents the wear test experimental results for different materials, including load, sliding velocity, sliding distance, time, RPM, track diameter, weight before and after the test, change in weight, mass wear rate, and coefficient of friction (COF).

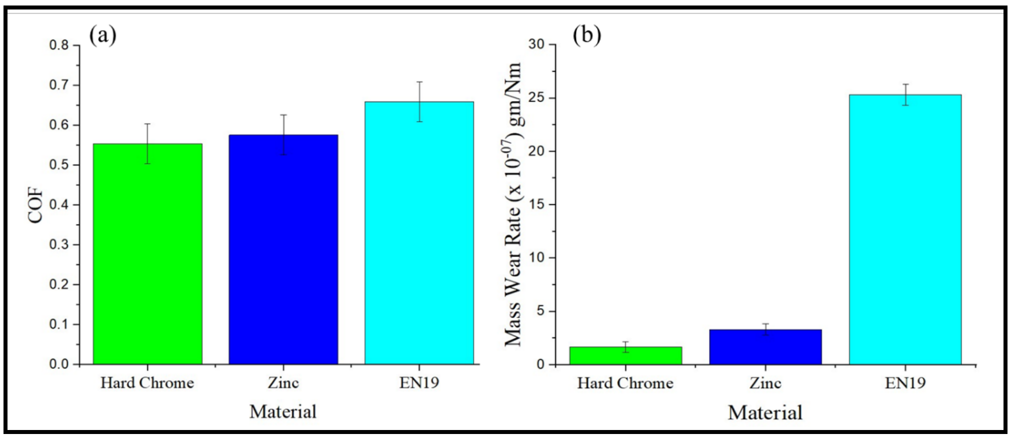


Figure 2 (a) COF obtained for Hardchrome, Zinc, EN19. (b) Mass Wear Rate obtained for Hardchrome, Zinc, EN19.

The EDS analysis results, conducted using the Quanta 200F machine from the Netherlands are as follows.

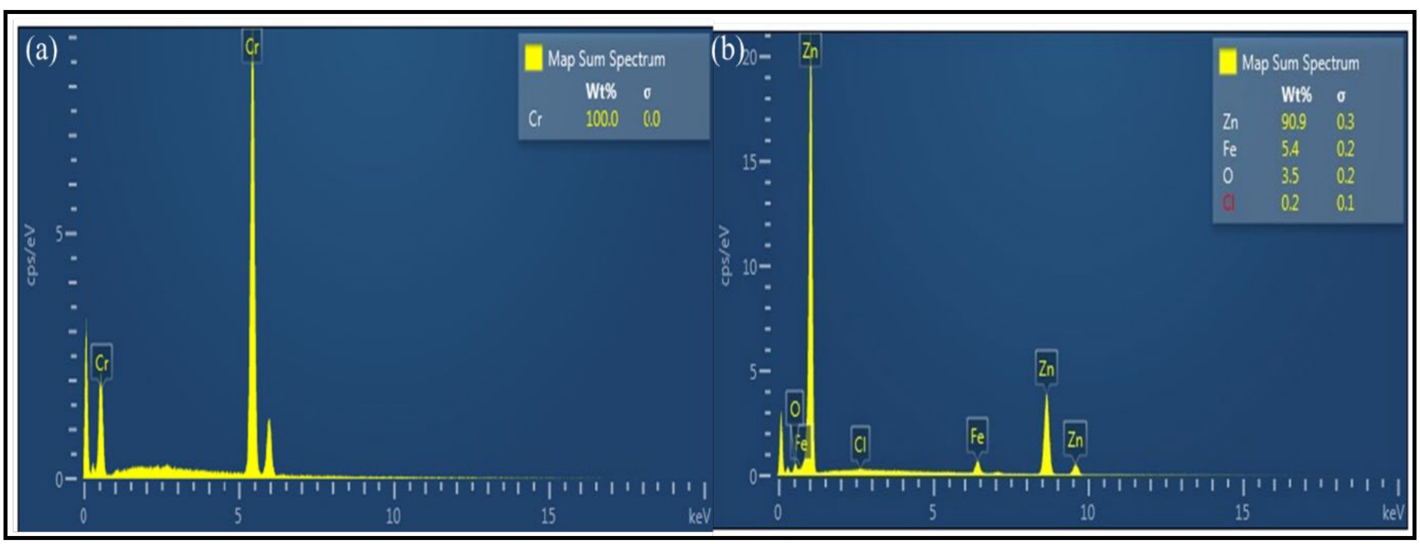


Figure 3 EDS graph for a) Hard chrome coating, (b) Zinc coating

The EDS Graph shown in figure 3(a) unmistakably validates the substantial presence of Hard chrome coating, constituting a 100% composition by weight. In this intriguing EDS Graph as shown in figure 3(b), the confirmation of zinc coating emerges. The composition is dominated by Zinc at 90.9%, accompanied by a 5.4% presence of Iron. Additionally, minor proportions of Oxygen and Chlorine are detected by weight, adding a nuanced complexity to the coating's composition.

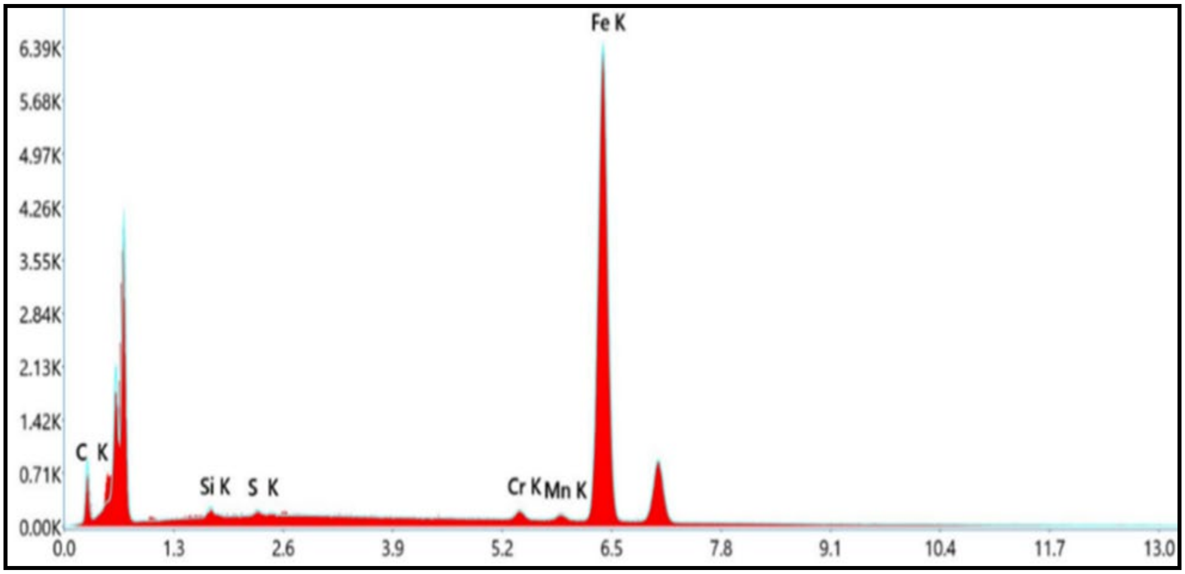


Figure 4 EDS graph for substrate EN19

Figure 4 displays the EDS analysis results which definitively establish the composition of EN19, the material from which the roll in the heavy steel industry is fabricated. The composition is as follows: Iron (72.9%), Carbon (25.3%), with trace amounts of Silicon, Sulphur, Chromium, and Manganese (ranging from 0.2% to 0.65%) by weight as depicted in Table 3.

Table 3 EDS Analysis for EN19 Composition

Element	Weight %	MDL	Atomic %	Net Int.	Error %	R	A	F
C K	25.3	0.76	61.0	132.1	12.5	0.8303	0.0684	1.000
Si K	0.4	0.09	0.4	37.3	17.6	0.8776	0.4338	1.0099
S K	0.2	0.10	0.2	20.7	27.8	0.8870	0.6531	1.0248
Cr K	0.6	0.15	0.3	49.3	17.1	0.9204	0.9600	1.5342
Mn K	0.6	0.27	0.3	27.6	23.4	0.9245	0.9688	1.1489
Fe K	72.9	0.29	37.8	3023.9	2.1	0.9286	0.9744	1.0259

This revised format presents the elements, weight percentages, minimum detection limits (MDL), atomic percentages, net intensities, error percentages, and additional relevant values in a clearer and organized manner.

In Figure 5, the FE SEM image, magnified at 100X, vividly illustrates the wear track that has developed on the EN19 substrate following the wear test. This wear track prominently exhibits the presence of pits and craters, which are indicative of wear resulting from both abrasive and adhesive mechanisms. It is evident from the SEM images that the EN19 substrate has experienced the most significant wear, as evidenced by the pronounced formation of pits and craters, when compared to both Hard chrome and Zinc coatings.

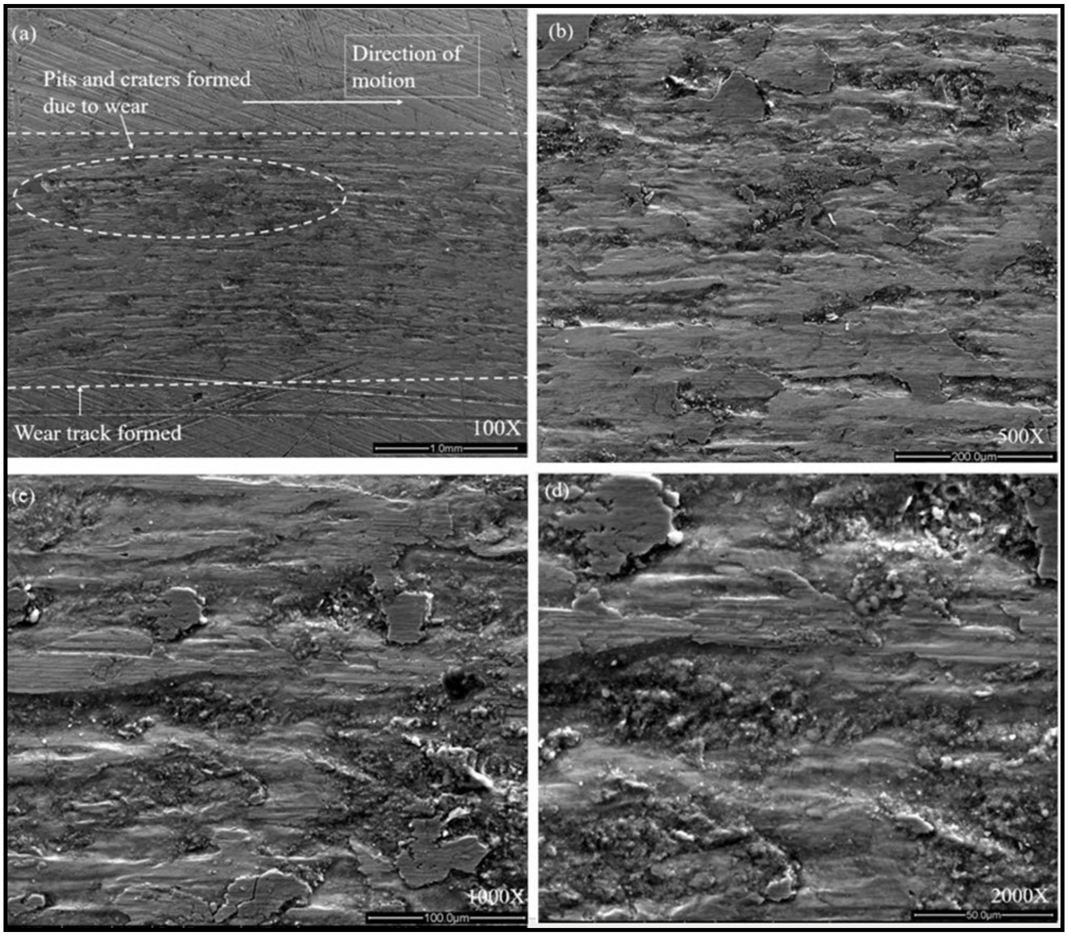


Figure 5 FESEM of EN19 inside the wear track at different magnification a) 100X, b) 500X, c)1000X, d) 2000X.

The depicted figure 6 offers a detailed view of the FESEM analysis conducted on the Hard chrome surface within the wear track that emerged following the wear test, captured at a substantial magnification of 200X. In this image, the presence of pits and craters becomes remarkably evident, and these features are key indicators of wear resulting from a combination of abrasive and adhesive mechanisms. The visual evidence presented in this SEM image underscores a significant observation: the degree of wear in the Hard chrome coating is notably lower when juxtaposed with images of the EN19 substrate.

In essence, this high-magnification SEM image not only confirms the presence of wear but also highlights the superior wear resistance of the Hard chrome coating in comparison to the EN19 substrate. This finding underscores the potential of Hard chrome as an effective protective coating for applications demanding enhanced wear resistance.

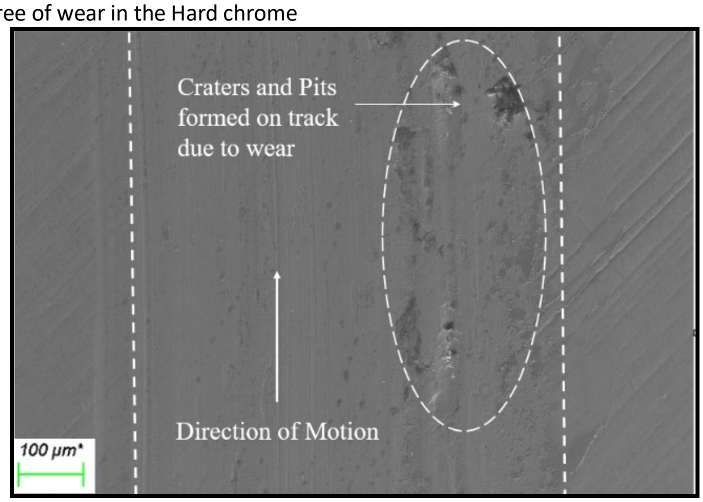


Figure 6 FESEM of Hard chrome wear track formed at 200X.

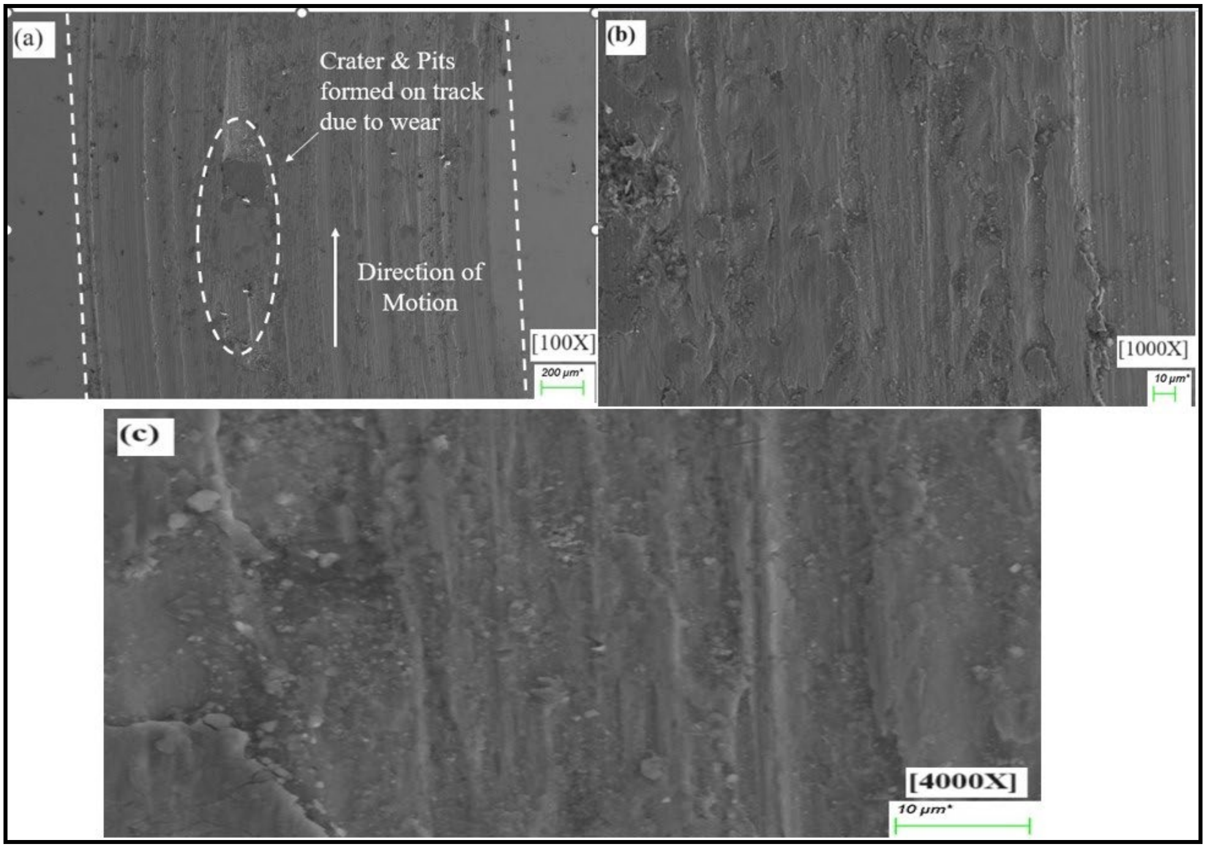


Figure 7 FESEM of Zinc at the wear track formed after wear test at different magnification, a) 100X, b) 1000X, c) 4000X.

In Figure 7, a series of images reveals the wear track that has materialized on the Zinc coating following the wear test, each captured at varying levels of magnification—100X, 1000X, and 4000X. These images distinctly illustrate the presence of wear, primarily resulting from a combination of adhesive and abrasive interactions. However, it is noteworthy that the observed wear on the Zinc coating is less pronounced when compared to that on the EN19 substrate [21-25].

By providing these detailed images at multiple magnification levels, Figure 7 effectively conveys the extent of wear experienced by the Zinc coating. Additionally, it emphasizes the significant contrast in wear between the Zinc coating and the EN19 substrate, affirming the protective qualities of the Zinc coating against wear, albeit to a lesser degree than the Hard chrome coating.

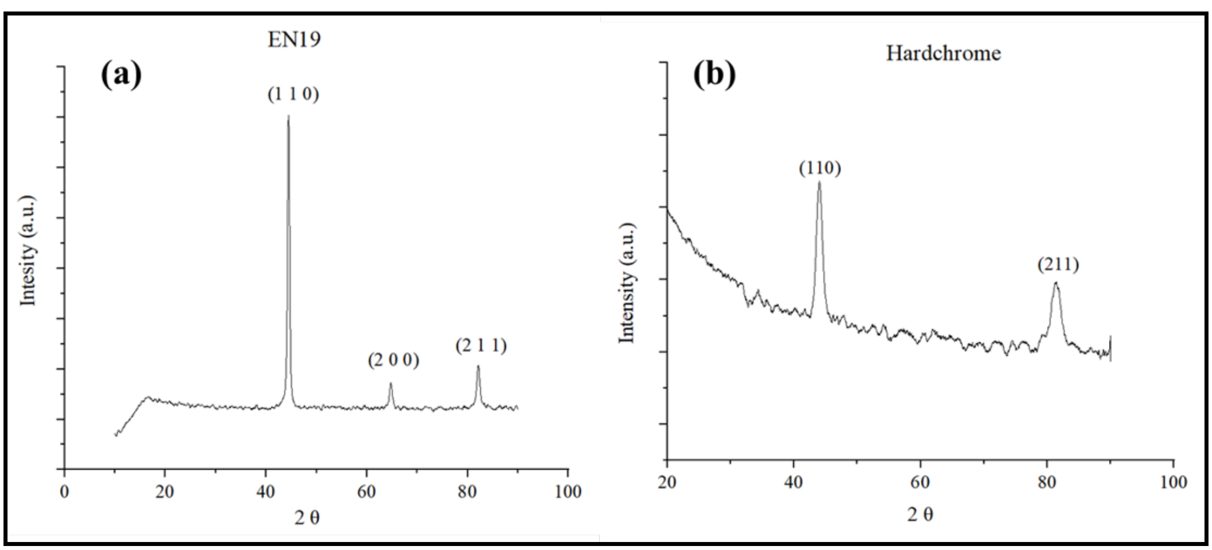


Figure 8 XRD graph for a) EN19 b) Hard chrome.

Figure 8(a) showcases the X-ray diffraction (XRD) graph, obtained using the D8 DISCOVER machine from Bruker, which pertains to the EN19 material. The graph exhibits distinct peaks that hold significant meaning. At 2θ=44.48, corresponding to the Fe (110) plane, there is a prominent peak with an intensity of 6582. Another notable peak emerges at 2θ=64.73 (intensity 2908.41), aligning with the Fe (200) plane. Lastly, at 2θ=82.14 (intensity 3099.87), a distinct peak corresponding to the Fe (211) plane is observed. Importantly, these observed peaks are in accordance with established standard references. Figure 8(b) displays the XRD graph pertaining to the Hard chrome (HC) coating. This graph has been analyzed in accordance with the literature survey and by comparing it to the standard diffraction peaks for chromium [13]. In the XRD graph, a distinctive peak corresponding to the HC (110) plane is observed at 2θ = 43.956, with an intensity of 1180.18. Additionally, another noteworthy peak aligns with the HC (211) plane at 2θ = 81.07, with an intensity of 1019.28. Importantly, these observed peaks closely match the standard diffraction peaks for chromium. An intriguing characteristic of this graph is the presence of narrow, sharp peaks. This feature is indicative of the crystalline nature of the Hard chrome coating. The sharpness of the peaks underscores the well-defined crystalline structure of the coating material, providing valuable insights into its composition and crystalline properties.

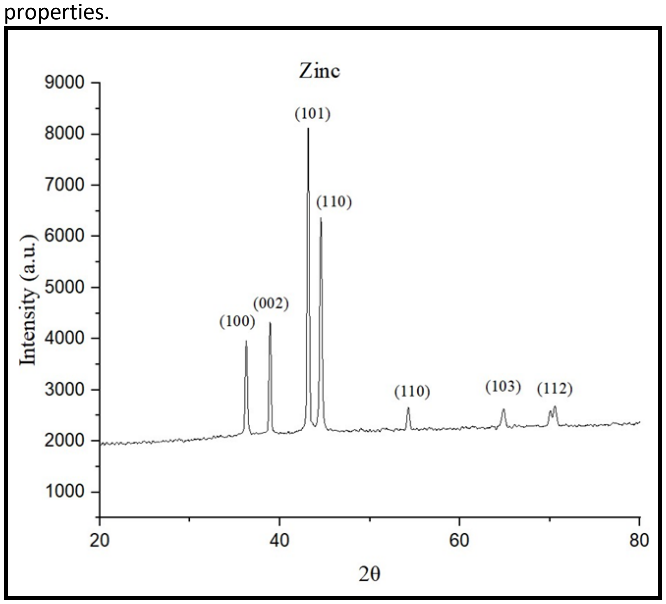


Figure 9 XRD graph for Zinc.

Figure 9 displays the X-ray diffraction (XRD) graph for the Zinc coating. Through a literature survey and comparison with standard diffraction peaks for zinc [7], several key findings have emerged. A peak corresponding to the Zn (100) plane is clearly visible at 2θ = 36.34, with an intensity of 3977.92. Another significant peak aligns with the Zn (002) plane at 2θ = 38.89, with an intensity of 4326.68. Further peaks corresponding to Zn (101), Zn (110), Zn (103), and Zn (112) planes are also evident. Importantly, this XRD graph demonstrates the presence of narrow, sharp peaks, while notably, no broad peaks are observed. These characteristics collectively signify that the Zinc coating maintains a crystalline nature, providing valuable insights into its structural properties. The X-ray diffraction (XRD) analysis of EN19, Hard chrome, and Zinc specimens reveals a consistent feature: the presence of narrow, sharp peaks, indicative of their crystalline structures. Additionally, the XRD results provide valuable information about the composition of the coated Zinc and Hard chrome on the EN19 substrate, further confirming the coating's composition. Notably, the XRD data indicates that the lattice parameters a, b, and c are not equal (a = 4.221, b = 4.09, c = 3.791), and the angles α, β, and γ are all 90 degrees (α = β = γ = 90°). This information suggests that the coatings exhibit a tetragonal symmetry with a slight monoclinic influence. In summary, the XRD analysis has elucidated the crystalline nature of the materials and provided insights into their structural characteristics, while also confirming the composition and symmetry of the coatings on the EN19 substrate.

4.0 CONCLUSION

The research addresses the issue of frequent wear and tear of rolls in dynamic rolling processes, leading to reduced efficiency and significant capital losses. The study explores the application of zinc and hard chrome coatings on the EN19 substrate to mitigate roll wear. The coatings are verified through rigorous analyses, including Energy Dispersive X-ray Spectroscopy (EDS) and X-ray Diffraction (XRD), which confirm their composition and crystalline nature. Experimental tests on a pin-on-disk wear machine yield mass wear rates, with hard chrome demonstrating exceptional performance. It outlasts the EN19 substrate by 15.19 times and zinc by a factor of two. Zinc also extends the substrate's lifespan by 7.6 times. Scanning Electron Microscopy (SEM) images reveal that adhesive and abrasive wear are the primary factors contributing to roll wear. The research concludes that hard chrome coating is an effective solution to substantially extend the life of rolls in rolling processes. This extension minimizes capital and time losses associated with roll wear. Additionally, hard chrome coatings offer the advantages of low friction and excellent corrosion resistance. The findings have practical implications for industries reliant on rolling processes, offering a cost-effective means of improving efficiency and reducing downtime due to roll wear.

In real use [26], the roll's diameter ranges from 60 to 400 mm, and its approximate length is 1400–1800 mm. 0.2 to 10 m/s is the roll speed. The rolled workpiece, which is typically made of low to medium carbon steel, has a width of 700–1500 mm and a thickness of 1.5–4 mm. About 0.3 and 0.15 static and dynamic friction are generated, respectively. The rolled workpiece and EN19 roll can create a maximum Hertzian contact pressure of 500–2500 MPa.

The same roll material, EN19, with a Poisson's ratio of 0.3, an elastic modulus of 200 GPa, and a hardness of 23 HRC, is chosen for this experiment. It was rubbed up against a Silicon Nitride ball with an elastic modulus of 166 GPa and a Poisson's ratio of 0.23. 1 m/s was chosen as the experimental velocity. Through a 30 N load, the Silicon Nitride ball and EN19 developed a maximum Hertzian contact pressure of 1500 MPa. Silicon Nitride, which is significantly harder than low to medium carbon steel, is used as the rubbing material in this experiment. In real life, rolled workpieces are made of low to medium carbon steel. Additionally, the experimental setup attempted to replicate the real situations.

The sample price for uncoated roll material EN19 of dia. 40 × 15 mm thickness is Rs. 100 whereas the coated zinc and hardchrome sample with 100-micron thickness coating has been Rs. 216 and Rs. 274 respectively. But, considering the life of zinc coating which is nearly 7.6 times the life of EN19 and hardchrome coating which has the life of 15.19 times the life of EN19, the coated zinc and hardchrome substrate turns out to be much cheaper than the EN19.

Also, as a possibility of future study, there is a scope to do more literature review for other materials and alloys other than hardchrome and zinc which can prove to have more longevity compared to others. The current research work can also be further extended by using Multi-Criteria Decision Making (MCDM) techniques such as WPM, SAW etc. methods, through which further validation can be done.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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