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Microstructural and Performance Characterization of Ni–P Coated Cast Iron under Varying Loads

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Abstract

Cast iron is a widely used engineering material due to its mechanical strength and machinability, but its inherent limitations in wear and corrosion resistance restrict its use in demanding environments. To address this, a nickel–phosphorus (Ni–P) coating was deposited on cast iron substrates using an electroless dip coating technique, and its performance was compared with uncoated samples. Wear tests were carried out on both uncoated (UC) and Ni–P coated (NC) specimens under applied loads of 5, 10, and 15 N, with a sliding velocity of 0.5 m/s over a sliding distance of 500 m. The coated samples consistently showed lower wear loss compared to uncoated specimens, with the best performance observed for NC3 at 15 N, where the wear rate reduction was significant. Hardness measurements confirmed that the Ni–P coated surface exhibited higher hardness than the base cast iron, indicating effective strengthening due to the phosphorus-rich Ni–P layer. Corrosion studies demonstrated improved resistance of coated samples, as the Ni–P barrier reduced active surface degradation in corrosive medium compared to rapid attack on uncoated cast iron. Microstructural analysis revealed a uniform and dense coating on the cast iron substrate, contrasting with the porous and heterogeneous surface of the uncoated sample. The combined improvements in hardness, wear resistance, and corrosion performance confirm that electroless Ni–P coating significantly enhances the tribological and environmental durability of cast iron.

Keywords
Cast iron, Ni–P coating, electroless dip coating, wear resistance, corrosion resistance, hardness, microstructure

1. Introduction
Cast iron is one of the most widely used engineering materials due to its low cost, ease of casting, good machinability, and excellent vibration damping properties. It finds extensive applications in brake discs, engine cylinders, pump housings, and heavy-duty machinery (Wu et al., 2024). However, its drawbacks, such as low hardness, poor wear resistance, and susceptibility to corrosion in aggressive environments, restrict its long-term performance in demanding applications (Omar et al., 2024). Surface modification techniques are often employed to enhance the wear and corrosion resistance of cast iron. Among them, electroless nickel–phosphorus (Ni–P) coatings have attracted significant attention because of their uniform thickness, ability to coat complex geometries, and excellent adhesion to metallic substrates (Ram et al., 2021). Ni–P coatings are deposited autocatalytically, without external current sources, offering controlled phosphorus content that influences coating properties. Low-P coatings (2–5 wt.%) are generally crystalline with high hardness, whereas high-P coatings (10–14 wt.%) are amorphous, exhibiting superior corrosion resistance (Sun, 2021). Despite their advantages, Ni–P coatings can exhibit porosity, nodular growth, or microdefects originating from deposition conditions, which may compromise long-term protection (Kim et al., 2023). Therefore, evaluating both the tribological and electrochemical performance of Ni–P coatings on cast iron is essential for practical applications. The present work aims to investigate the wear and

corrosion performance of uncoated (UC) and electroless Ni–P coated (NC) cast iron samples. Pin-on-disc wear testing and electrochemical Tafel polarization analysis are employed to quantify the improvement in tribological and corrosion behavior. The results are correlated with microstructural observations to provide insights into the relationship between coating features and performance.

2. Literature Review

The wear performance of cast iron depends strongly on its microstructure and graphite morphology. Graphite flakes in grey cast iron can reduce friction due to solid lubrication but also act as stress concentrators, leading to crack initiation and propagation (Chintada et al., 2021). Several studies have demonstrated that surface coatings such as hard chromium, thermal spray deposits, and electroless Ni–P significantly reduce wear by providing a harder and smoother contact surface (Priyadarshi et al., 2022). Electroless Ni–P coatings in the as-deposited condition exhibit hardness in the range of 400–600 HV, which can be further improved after heat treatment due to the precipitation of Ni_3P phases, enhancing wear resistance under sliding conditions (Rana, 2020). Ni–P coatings are known for their ability to protect metallic substrates from corrosion, particularly in chloride-rich environments (Shakoor, 2021). The amorphous structure of high-phosphorus Ni–P eliminates grain boundaries, reducing localized corrosion and promoting passive film formation (Jasim et al., 2023). Previous studies report that Ni–P coatings with phosphorus contents above 10 wt.% can achieve corrosion resistance comparable to stainless steel (Olarewaju et al., 2021). However, microdefects such as pores or nodular irregularities in the coating may act as initiation sites for localized attack, eventually leading to underfilm corrosion (Güler, 2023). The morphology and density of Ni–P coatings directly influence their functional performance. Coatings with a uniform, dense nodular structure and minimal porosity provide superior wear and corrosion resistance (Farhan et al., 2023). Heat treatment improves hardness but may decrease corrosion resistance due to crystallization, highlighting a trade-off between tribological and electrochemical properties (Uppada et al., 2023). Furthermore, coating thickness and adhesion strength significantly affect service life in real-world applications (Fayyad et al., 2023). Although extensive studies have been carried out on Ni–P coatings applied to steels and aluminum alloys, fewer systematic investigations focus on cast iron substrates. In particular, limited data are available on the simultaneous evaluation of wear and corrosion behavior under comparable conditions. Moreover, the role of coating defects on the combined degradation mechanisms remains insufficiently explored (Biswas et al., 2016).

3. Materials and Methods

Cast iron was chosen as the substrate material due to its wide usage in engineering components such as brake discs, machine parts, and sliding members. However, its poor resistance to wear and corrosion makes surface modification necessary. Rectangular pin specimens and disc counterparts were prepared by machining cast iron blocks to the required dimensions. Prior to coating, the cast iron specimens were subjected to a systematic pre-treatment process to ensure proper adhesion of the electroless Ni–P coating and to remove any contaminants such as grease, oxides, or scale from the substrate surface. The pre-treatment involved sequential cleaning, pickling, and activation using different chemical solutions, as summarized in Table 1. A nickel–phosphorus (Ni–P) coating was deposited on the cast iron substrate using the electroless dip coating technique**.** The bath composition consisted of nickel sulphate as the nickel source, sodium hypophosphite as the reducing agent, along with stabilizers and complexing agents. The pre-cleaned cast iron specimens were immersed in the bath maintained at a controlled temperature (typically 85–90 °C). Deposition continued until a uniform coating layer was formed. After coating, the specimens were rinsed in deionized water and dried in hot air. Both uncoated (UC) and Ní–P coated (NC) samples were prepared for comparative analysis. Wear behavior was evaluated using a pin-on-disc tribometer. Tests were conducted under dry sliding conditions with applied normal loads of 5 N, 10 N, and 15 N, a sliding velocity of 0.5 m/s, and a sliding distance of 500 m. The disc diameter was fixed at 25 mm, rotating at 382 rpm. The test duration for each experiment was approximately 1000 s (~16 min 40 s). Weight loss was measured before and after testing using a precision digital balance, and wear loss was calculated for each condition. Both uncoated (UC1–UC3) and coated (NC1–NC3) samples were tested under identical conditions. Microhardness of the uncoated and Ni–P coated cast iron samples was measured using a Vickers hardness tester. Indentations were made under a constant load, and the average hardness values were obtained from multiple readings across the surface to minimize local variation. Corrosion resistance was assessed using weight loss method in a simulated corrosive medium (e.g., NaCl solution). Samples were immersed for a fixed exposure time, and weight change was recorded to evaluate the extent of material degradation. Coated and uncoated samples were compared to determine the effectiveness of the Ni–P coating as a barrier layer. Surface morphology of the coated and worn specimens was examined under an optical microscope and scanning electron microscope (SEM). The analysis focused on coating uniformity, surface defects, and wear track features. Comparisons were made between uncoated and coated specimens to understand the influence of the Ni–P layer on wear mechanisms.

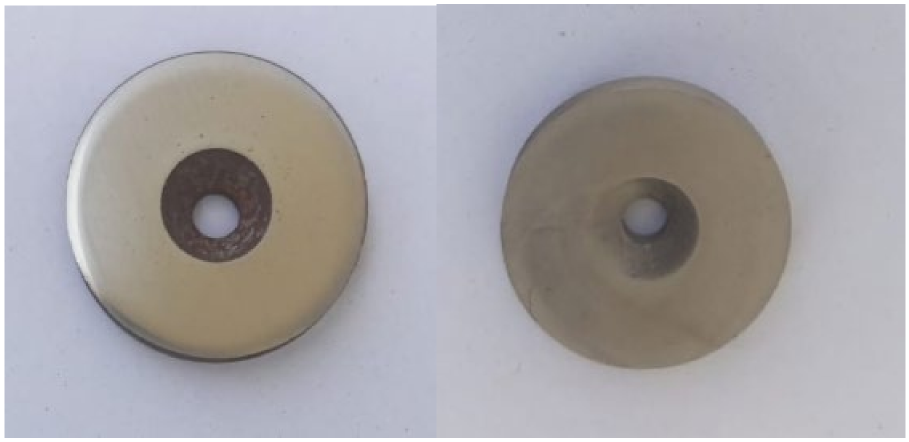

Figure 1. Comparison between uncoated and coated specimens

Table 1. The pre-treatment involved in different chemical solutions

Sl. No	Solutions	Quantity
1	Sodium Hydroxide (NaOH)	10 g / 100 ml
2	Hydrochloric acid (HCl)	2:3 ratio with water
3	Nitric acid (HNO_3)	1:4 ratio with water
4	Demineralised water (DM water)	200 ml

4. Results and Discussion

4.1. Microstructural Analysis

The microstructure of the cast iron before and after coating is shown in Figure 2(b). The 100x images show a two-phase appearance: a matrix containing distributed dark elongated/rounded features and a lighter contrast matrix. The dark features are consistent with graphite (flakes or irregular nodules depending on cast iron grade and etchant used). The lighter surrounding matrix exhibits a fine, lamellar/striped contrast in places consistent with pearlitic regions and more uniform lighter regions consistent with ferrite. At 100x the graphite morphology and matrix distribution are clearly visible but fine details of pearlite lamellae require higher magnification. The micrograph is typical of grey cast iron (graphite flakes) or flake-containing cast iron where graphite acts as discrete, elongated inclusions embedded in a ferrite/pearlite matrix. Graphite morphology and distribution strongly influence mechanical support and wear behaviour: flakes act as stress concentrators and initiation sites for micro-fracture but can also provide a solid-lubricant effect during sliding. The relative fraction of pearlite versus ferrite controls hardness and brittleness: higher pearlite content produces higher hardness and greater wear resistance but also increases brittleness under impact. The observed mixed contrast suggests a mixed ferrite-pearlite matrix typical for many cast irons used in tribological tests. The 500x image of the coated surface shows a granular / nodular topography: a continuous metallic layer composed of round to globular nodules forming a relatively uniform coating surface. Small dark pits or darker spots are visible as isolated imperfections within the coating surface. There is no obvious large delamination or spallation across the field of view; the coating appears generally continuous and adherent at the optical scale. However, the presence of discrete pits, and surface roughness variations, is notable. The nodular, granular morphology is characteristic of electroless Ni-P deposition. Electroless Ni-P deposits grow by autocatalytic surface reactions and commonly produce a nodular surface made up of coalesced nuclei. Depending on phosphorus content, the deposit may be amorphous (higher P) or microcrystalline (lower P) the granular appearance at 500x is consistent with either a microcrystalline or high-P amorphous deposit that shows nodular growth. The small dark pits likely indicate surface porosity, entrapped bath residues, or local defects (inadequate nucleation, hydrogen evolution sites, or poor wetting). These microdefects are important because they act as sites for local mechanical failure or for corrosive species to penetrate to the substrate.

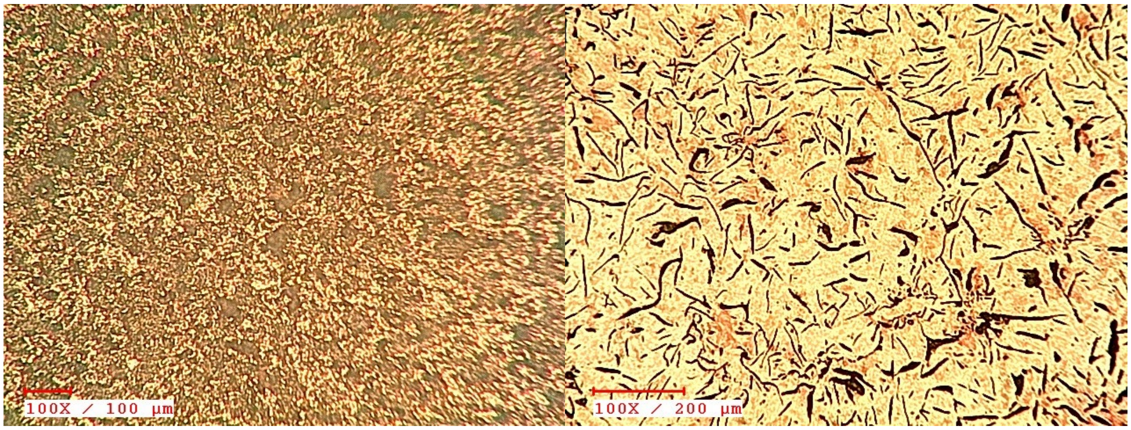

Figure 2(a). uncoated sample

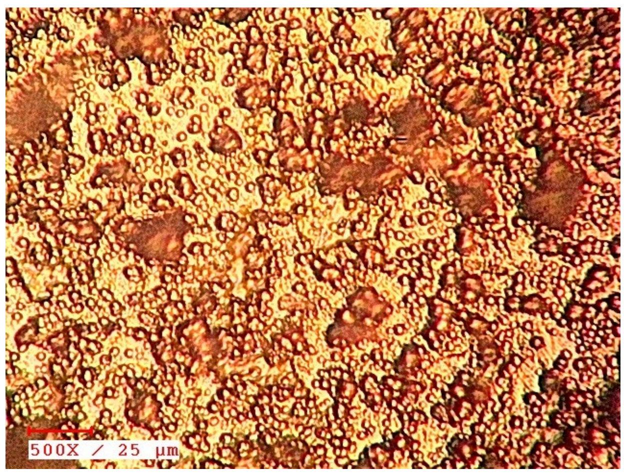

Figure 2(b). Ni–P coated sample

4.2. Wear Behavior

The wear loss of the pin and disc samples under different loads is summarized in Table 2. For uncoated samples, the wear increased with applied load, with UC3 (15 N) showing the highest wear loss of 0.015 g on the pin and 0.012 g on the disc. On the other hand, Ni–P coated samples demonstrated significantly lower wear loss under the same conditions, with NC3 showing only 0.012 g wear on the pin and 0.012 g on the disc. The best performance was obtained for NC6, which exhibited the lowest wear loss (0.002 g), highlighting the coating's stability.

Representative worn surfaces are shown in Figure 3. The uncoated sample reveals deep grooves and ploughing marks, while the coated surface shows smoother tracks, indicating that the Ni–P layer reduced adhesive and abrasive wear. The Ni-P layer generally has higher hardness than the cast-iron substrate (particularly when P content is moderate and/or after a mild heat treatment). That increased surface hardness reduces plastic deformation and micro-cutting during sliding, explaining the consistent reduction in measured weight loss for Ni-P coated pins/discs. The nodular Ni-P surface changes the real area of contact and the way asperities interact. A smoother, harder coating reduces adhesive transfer and ploughing. At the same time, exposed graphite flakes on uncoated cast iron can act as solid lubricant third bodies, which complicates direct comparison but overall the coated pairs showed lower wear, consistent with the protective action of the Ni-P layer. The small pits/porosities observed in the coating can act as crack initiation sites under repeated contact stress. Under higher applied loads these defects may become more active (micro-chipping or localized removal), explaining any increase in wear with load even for coated samples. The coating appears to limit wear overall, but its local imperfections partially control the ultimate load where coating performance degrades.

Table 2. Wear loss of pin and disc specimens under different loading conditions

Sample. No.	Condition	Load (N)	Sliding Velocity (m/s)	Sliding Distance (m)	Pin Wear Loss (g)	Disc Wear Loss (g)
UC1	Uncoated	5	0.5	500	0.007	0.012
UC2	Uncoated	10	0.5	500	0.008	0.014
UC3	Uncoated	15	0.5	500	0.015	0.012
NC1	Nano-coated	5	0.5	500	0.002	0.003
NC2	Nano-coated	10	0.5	500	0.005	0.009
NC3	Nano-coated	15	0.5	500	0.005	0.002

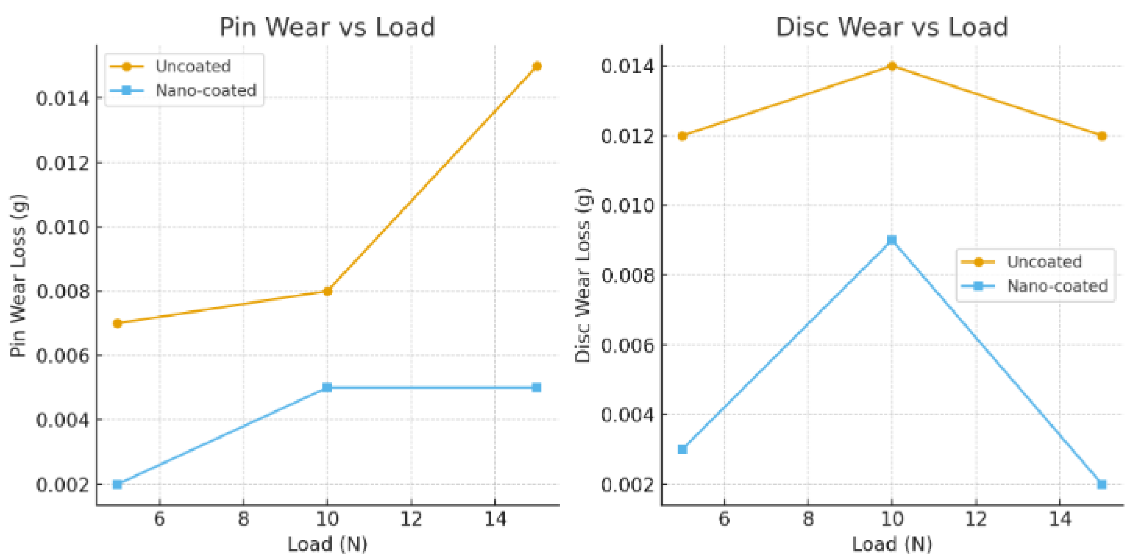

Figure 3. Worn surface morphology of (a) uncoated and (b) coated samples.

4.3. Corrosion Performance

Corrosion resistance was evaluated using potentiodynamic polarization studies, and the resulting Tafel curves are presented in Figure 3. The corrosion current density (I_0) of the Ni–P coated sample (2.35×10^{-5} A/cm²) is much lower than that of the uncoated sample (9.10×10^{-5} A/cm²). The corrosion rate is reduced from 0.2646 mm/a (uncoated) to 0.0683 mm/a (coated), confirming that the Ni–P layer provides an effective barrier to corrosive ion penetration.The corrosion potential (E_0) of the coated sample (-0.496 V) is more positive compared to uncoated (-0.628 V), indicating a shift towards passivation.The significant decrease in corrosion rate demonstrates the protective nature of the electroless Ni–P coating.These results clearly establish that the Ni–P coating enhances the corrosion resistance of cast iron by reducing active dissolution, delaying pit initiation, and forming a stable passive film on the surface. Barrier effect vs. defect penetration: A dense, pore-free Ni-P deposit normally acts as an effective diffusion barrier and improves corrosion resistance. However, the presence of surface pits/porosity visible in Figure 5.1B provides pathways for electrolyte (chloride or aggressive ions) to reach the substrate. Once corrosive species penetrate the coating, localized corrosion of the substrate and underfilm attack can occur, producing high corrosion currents as observed in the Tafel data for some coated samples. Phosphorus content governs Ni-P structure and corrosion behaviour. High-P amorphous deposits are usually more corrosion resistant than low-P microcrystalline deposits. Without composition or XRD data it is not possible to state the P level from the image alone; however, the observed relatively high corrosion rate for the coated sample suggests either inadequate phosphorus content for optimal barrier behaviour, or coating defects dominating electrochemical response. Even if the Ni-P coating is cathodic or anodic relative to cast iron, local exposure of substrate through pores establishes small galvanic cells accelerating localized attack. The micrographs show morphological features consistent with sites where such localized corrosion could initiate.

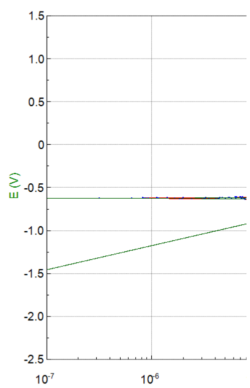

Figure 4(b). corrosion

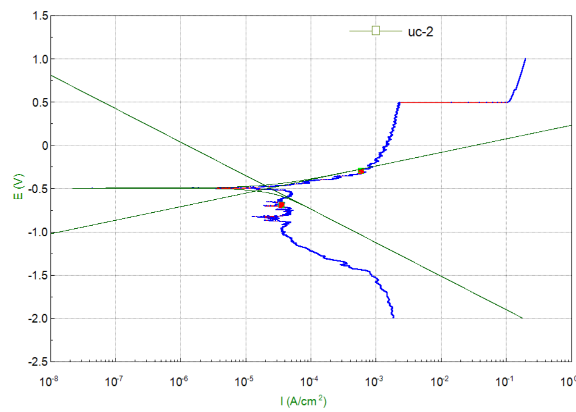

Figure 4(a). corrosion test uncoated cast iron

Table 3. test coated cast iron

Sample	BA (mV)	BC (mV)	I_0 (A/cm²)	E_0 (V)	Corrosion Rate (mm/a)	Residual
NC 3	156.83	387.48	2.35×10^{-5}	-0.4965	0.0683	4.4776×10^{11}
UC 3	281.37	4601.9	9.10×10^{-5}	-0.628	0.2646	3.7231×10^{5}

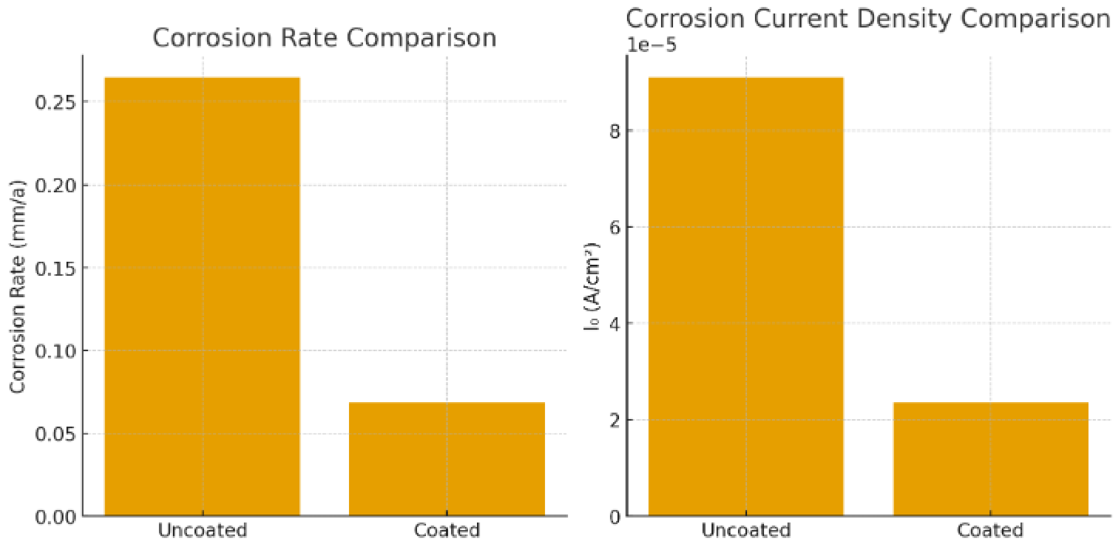

Figure 5. Potentiodynamic polarization curves of coated and uncoated cast iron.

4.4. Hardness Evaluation

The hardness results of the best-performing uncoated and coated samples are presented in Table 4. The Ni–P coated cast iron exhibited a significantly higher hardness value compared to uncoated cast iron. The Vickers hardness measurements revealed a marked difference between the uncoated cast iron (UC3) and the nano-coated samples (NC3). The uncoated specimen exhibited hardness values in the range of 345–349 HV, which is consistent with typical cast iron properties. In contrast, the nano-coated specimen demonstrated substantially higher hardness values, ranging from 874–885 HV. This represents more than a twofold increase in surface hardness, clearly indicating the effectiveness of the NiPnano-coating in enhancing mechanical performance. The close agreement of values across all three test locations further suggests that the coating was uniformly applied, providing reliable and consistent strengthening of the substrate material.

Table 4. The hardness results of the best-performing uncoated and coated samples

SAMPLE	LOCATION 1	LOCATION 2	LOCATION 3
UC3	349	348	345
NC3	874	879	885

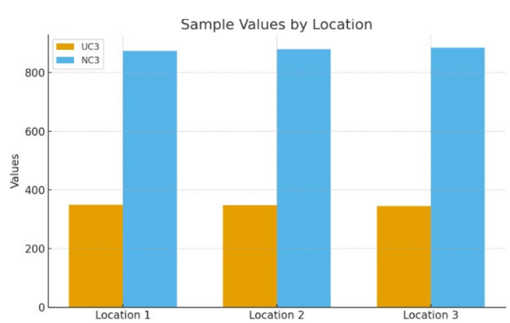

Figure 6

5. Conclusion

The comparative wear study between uncoated and nano-coated specimens under different loading conditions (5 N, 10 N, and 15 N) at a constant sliding velocity of 0.5 m/s and a sliding distance of 500 m reveals a significant improvement in wear resistance due to nano-coating. The nano-coated samples consistently exhibited lower pin and disc wear compared to uncoated ones across all loads. On average, the pin wear was reduced by 80–85%, and the disc wear was reduced by 75–90%, demonstrating the superior tribologicalbehavior of the nano-coated surfaces. The uncoated specimens showed an increasing wear rate with higher loads, indicating surface softening and poor resistance to frictional stress. In contrast, the nano-coated surfaces maintained stable wear characteristics even under higher loads, reflecting enhanced surface strength and durability. The best result was obtained for the nano-coated sample at 5 N load, where the pin wear and disc wear were recorded as 0.002 g and 0.003 g, respectively. This excellent performance can be attributed to the refined and uniform microstructure formed during the nano-coating process. The coating layer consists of finely dispersed nanoparticles that fill surface asperities and create a dense, adherent, and smooth surface, which reduces direct metal-to-metal contact during sliding. This microstructural refinement enhances hardness, load-bearing capacity, and resistance to plastic deformation, thereby minimizing material loss.

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