Development of High-Performance Coatings for Corrosion Protection of Structural Materials

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Abstract:

In many sectors, corrosion is a major problem because it causes structural damage, safety issues, and monetary losses. High-performance coatings have become a potentially effective method for preventing corrosion in structural materials. The creation of high-performance coatings requires a multidisciplinary strategy that integrates engineering, chemistry, and materials science. Designing coatings with exceptional barrier qualities, adhesive power, and resilience to environmental variables has been a research priority. To improve coating performance, cutting-edge materials such Nano composites, organic-inorganic hybrids, and self-healing polymers have been investigated. In order to obtain exact coating thickness and uniformity, new deposition processes such plasma spraying, chemical vapour deposition, and electrochemical approaches have also been used. High-performance coatings have proven to be incredibly effective at preventing corrosion in structural materials. They successfully serve as a physical barrier that keeps corrosive species from penetrating the substrate below. These coatings can also emit corrosion inhibitors or have self-healing qualities, which increases their capacity for protection. Scalability, cost-effectiveness, and environmental sustainability continue to be issues, nevertheless. In this paper discussed high-performance coatings have become a crucial component of structural material corrosion prevention. Their outstanding performance, combined with ongoing developments, offers tremendous promise for reducing corrosion-related problems and guaranteeing the durability of vital infrastructure across numerous industries. This research explores the corrosion resistance of several Nano scale microstructures within a particular material system with the goal of developing high-performance materials in a novel way.

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I. Introduction

The improvement of microstructure, nanocrystallization, and amorphism have become well-known techniques over the past two decades for producing materials with extraordinary performance and distinctive features. The development of super steel towards the close of the previous century is a significant example. Super steel displayed greatly improved tensile strength and yield strength by using methods including fine crystallisation, alloying, and purification. As a result, compared to conventional steel, super steel's strength and lifespan were doubled.

Additionally, some metals with nanocrystalline grains have shown extremely high strengths greater than 2 GPa. For instance, face-centered cubic single phase nanocrystalline nickel-cobalt solid solutions have excellent ductility with an elongation before failure of about 16 percent and outstanding tensile strengths of about 2.3 GPa. The problem of increasing the strength, hardness, and longevity of structural materials yet remains, despite the successful study and production of super steel. The ongoing discovery of maritime resources makes this problem much more important because the materials used to make engineering equipment must have outstanding corrosion resistance. In addition, determining a material's long-term corrosion resistance is challenging due to the complexity of deep-sea settings, and there is little information on whether super steel's corrosion lifespan can be increased by more than double. In order to produce high-performance materials with remarkable wear resistance and simultaneous corrosion resistance, our team has proposed a novel strategy. With the help of this technique, we may take advantage of the high strength provided by nanocrystalline materials and the superior corrosion resistance offered by amorphous materials by creating a composite microstructure out of nanocrystalline and amorphous phases.

This method also has the benefit of lessening the difficulties brought on by nanocrystalline materials' low corrosion resistance and amorphous materials' excessive brittleness. It is challenging to compare the correlation between microstructure and characteristics because it is challenging to produce materials with various microstructures within the same material system. In this study, we prepared Ni-P alloy coating materials with nanocrystalline, amorphous, and amorphous-nanocrystalline composite microstructures in order to address this problem. Previous studies have shown that the phosphorus (P) content can control the Ni-P alloy's microstructure, from crystalline to amorphous states. Our research revealed that the structure of the electrodeposited Ni-P coatings gradually changed from microcrystalline to amorphous as the amount of phosphorus (P) in the coating layer increased. Several plating parameters, including current density, electrolyte phosphate concentration, pH level, electrolyte composition, and temperature, have an impact on this structural transition. We were able to create Ni-P coatings with various phosphorus concentrations and associated structures by varying these parameters.

Based on the amount of phosphorus in the Ni-P alloy, we have distinguished three different types of coatings in our prior research. The coating displays a crystalline structure when the phosphorus level is less than 5.2 weight percent. The coating exhibits an amorphous and nanocrystalline composite structure for phosphorus values ranging from 5.2 to 10.2 wt%. Last but not least, the coating primarily exhibits an amorphous form when the phosphorus level is above 10.2 weight percent. Comparing the corrosion resistance of these three various types of coatings is the primary goal of this study. In order to do this, we used electrodeposition to create coatings on low carbon steel with nanocrystalline, amorphous-nanocrystalline hybrid, and amorphous microstructures. We were able to produce the appropriate coating structures by adjusting the pH value and current density during the electro deposition procedure.

We measured the coatings' composition, looked at the surface shape, and examined the microstructure to characterise them. We also performed a number of high-pressure immersion corrosion tests and electrochemical corrosion testing. We varied the hydrostatic pressure during the immersion trials in light of its impact on marine habitats. We sought to evaluate and compare the corrosion resistance of the coatings with various microstructures using these experimental techniques. We can learn more about the efficiency of each coating type in preventing corrosion by examining the outcomes. These discoveries will aid in the creation of high-performance materials with enhanced corrosion resistance for use in marine applications.

II. Various Types of Methods for Corrosion Protection

A) Corrosion Protection Techniques:

For structural materials, there are numerous sorts of corrosion protection techniques. Here are a few typical categories along with a brief description of each:

1. Barrier Coatings: A physical barrier is created by barrier coatings between the structural material and the corrosive environment. They shield the substrate from corrosion by preventing the corrosive substances from getting to it. Paints, epoxy coatings, and powder coatings are a few examples of barrier coatings.
2. Sacrificial Coatings: Sacrificial coatings, sometimes referred to as sacrificial anodes or cathodic protection, use a more reactive metal that corrodes more favourably to safeguard the structural material. The structural material is attached to the sacrificial metal, which corrodes in a way that slows down corrosion on the substrate. Commonly utilised sacrificial metals include magnesium, aluminium, and zinc.
3. Cathodic Protection: Cathodic protection is a technique for preventing corrosion in metal by using electrical currents. The structure is turned into a cathode by applying direct current to it, which also lowers the structure's corrosion potential. For reinforced concrete, offshore constructions, and underground pipelines, this method is frequently employed.
4. Corrosion inhibitors are chemicals that are introduced to corrosive environments in order to lessen or stop corrosion. They function by creating a shielding coating on the metal surface that serves as a defence against corrosive substances. Inhibitors can be sprayed on as liquids, coated on surfaces, or built into the substance itself.
5. Coating Modification: This technique entails changing the coating's characteristics to improve its ability to resist corrosion. It might entail including self-healing substances, nanocomposites, or corrosion inhibitors in the coating matrix. The coating's adherence, barrier qualities, and capacity to withstand chemical attack can all be improved by modification. A passive oxide layer is created during the process of passivation, which shields a metal's surface from corrosion. Aluminium and stainless steel are frequently used with it. Chemical processes that encourage the production of the protective oxide layer, such as acid pickling or exposure to oxidising chemicals, can be used to passivate materials.
6. Environmental Modification: To reduce corrosion, this strategy modifies the environment around the structural material. Controlling humidity, temperature, pH, or exposure to corrosive gases are a few examples. The corrosive attack on the material can be lessened or stopped by changing the environment.

B) Factor consideration:

1. Material Type: The susceptibility of various materials to corrode varies. For instance, non-metallic materials like concrete and polymers have their own mechanisms for degradation while metals like steel, aluminium, and copper are susceptible to corrosion. The individual material being utilised will

determine the method of corrosion protection to be applied.

2. Environmental Conditions: Choosing the best corrosion prevention strategy requires careful consideration of the structure's operating environment's corrosive conditions. The rate of corrosion can be considerably impacted by variables like humidity, temperature, chemical presence, and exposure to saltwater or industrial contaminants.
3. Desired Service Life: An important factor to take into account is the structure or component's intended service life. While some corrosion prevention techniques are long-lasting, others could need routine upkeep or replacement. The choice should be in accordance with the anticipated lifespan of the building and the desired level of required maintenance.
4. Cost considerations: Choosing a corrosion protection strategy requires careful consideration of the associated costs. Considerations should be made for the initial cost of the materials, their application or installation, continuing maintenance costs, and the potential for future repairs or replacements. Finding a balance between the method's efficacy and its economic viability is crucial.
5. Aesthetics: In some circumstances, the structure's outward look may be taken into account. Corrosion protection techniques that offer decorative coatings or finishes may be favoured for situations where aesthetics are crucial, such as architectural buildings or consumer goods.

In order to choose the best corrosion protection strategy that offers efficient defence, satisfies durability requirements, fits the budget, and ensures adherence to pertinent standards and regulations, it is ultimately necessary to carefully evaluate these factors. The various approaches are discussed and summarized in table 1.

Table 1: Summary of Several methods for the creation of high-performance coatings for the prevention of corrosion in structural materials

Methodology/ Approaches	**Meaning**
Coatings made of Nano crystals	Nano crystallinemicrostructure coatings that improve corrosion resistance and mechanical strength.
Amorphous Coating	Amorphous microstructure coatings offer superior corrosion resistance and barrier qualities.
Self-Healing Coatings	Coatings with the capacity to patch up minor flaws or cracks on their own while continuing to provide protection over time.
Composite Coating	Coatings that strike a balance between mechanical strength and corrosion resistance by combining Nano crystalline and amorphous phases.
Layer Coating	Coatings containing numerous functional layers, such as barrier layers, corrosion inhibitors, and adhesion promoters, are referred to as multilayer coatings.
Hybrid Approach coating	Hybrid Organic-Inorganic Coatings: Coatings that blend organic and inorganic components to improve mechanical strength, barrier characteristics, and corrosion resistance.
Nanostructured Coatings	Coatings that have a carefully planned arrangement of nanoscale components, like nanoparticles or nanotubes, to improve their mechanical and corrosion resistance.
Electrochemical Coatings	Coatings that are applied using electrochemical processes, such as

	electrodeposition or electroless plating, in order to acquire the desired characteristics and a regulated thickness.
Coatings for Conversion Coatings	Such as phosphate or chromate conversion coatings, that change the substrate's surface chemically into a corrosion-resistant layer.

III. Material and Method

An electrochemical cell is used to create electrochemical coatings. It is made up of a reference electrode, a counter electrode, and a working electrode (the substrate to be coated). An external power source is connected to the cell, which is submerged in an electrolyte solution, to permit electrodeposition. During the coating process, devices like a potentiostat or galvanostat are utilised to regulate the applied voltage or current. Low carbon steel (Q235) substrates with measurements of 10 mm x 10 mm and a thickness of 2 mm were employed during the electroplating procedure.

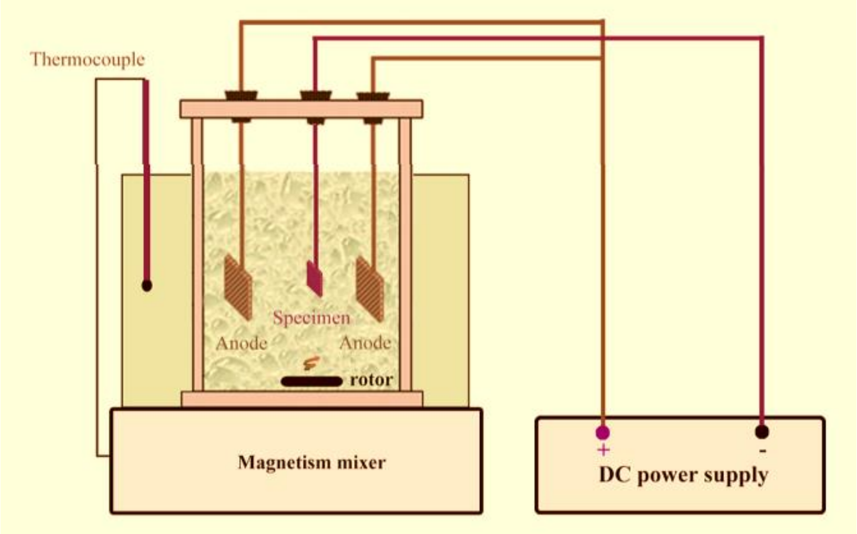

Figure 1: Illustration of the instrument's schematic.

In the plating configuration, the negative electrode was positioned 3 cm horizontally away from two pure nickel (99.99%) anodes. A magnetic rotor revolved steadily at the bottom of the plating tank. The substrates underwent a number of pre-treatment procedures to get them ready for electroplating. To provide a clear and smooth surface, the samples were first abraded using sandpapers up to 1000 grit. Following acetone degreasing, they underwent ultrasonic cleaning in deionized water. The specimens were then pickled and activated to get rid of any leftover impurities and encourage adhesion as shown in figure 1. The electroplating bath used for the procedure needed to have the pH value continuously adjusted by adding sulfuric acid solution to keep it stable. An electroplating current density of 25 to 66 mA/cm2 was used, and a pH range of 0.7 to 1.5 was maintained. Based on earlier research, the electroplating solution contained boric acid (32 g/L), nickel sulphate (220 g/L), nickel chloride (27 g/L), phosphoric acid (5 g/L), and an emulsifier (38 ppm).

An apparatus for field emission scanning electron microscopy (SEM), especially the SUPRA55 model from the USA, was used to investigate the surface of the deposited samples. This made it possible to characterise and image in great depth the topography and surface characteristics of the coating. Energy-dispersive spectrometry (EDS), which provided details on the elemental composition and distribution within the coating, was also used to determine the composition of the deposited sample. Transmission electron microscopy

(TEM) was used for a more thorough investigation of the microstructure morphology. The Tecnai G2 F28 equipment running at 220 kV was used for the TEM analysis, enabling high-resolution imaging and examination of the coating's interior microstructure and grain boundaries. Using Cu K radiation and the Bruker D8 Discover system, an X-ray diffraction (XRD) examination was performed to determine the grain size of the deposited sample. This method allowed for the determination of the coating's grain size as well as information on the crystallographic structure. These characterisation approaches could be used to gain a thorough understanding of the surface morphology, content, microstructure, and grain size of the coatings, assisting in the evaluation of their characteristics and effectiveness for preventing corrosion of the structural components.

The samples were cleaned with deionized water following the immersion experiment. Brushing was used to remove any corrosion products from the samples' surface, and then ultrasonic cleaning in deionized water was used to provide a clean surface for additional analysis. The weight of the corrosion samples after standardisation and preparation allowed us to gauge the degree of corrosion. Three-electrode cells were used to assess the resistance to electrochemical corrosion. Only one exposed end surface, with a surface area of roughly 1 cm2, was left for contact with the corrosion medium after the working electrodes were sealed with epoxy resin. The reference electrode was a saturated calomel electrode, while the auxiliary electrode was a platinum (99.9%) counter electrode. Using a CHI660E machine, corrosion experiments were carried out in a 3.8 wt% NaCl solution. To ascertain the corrosion characteristics of the produced NiP coatings, potentiodynamic polarisation tests were conducted. In order to quantify the corrosion behaviour under applied potentials, the scan rate for the polarisation experiments was adjusted to 1 mV/s. After calibrating the films to the instrument specifications, the open-circuit potential (OCP) of the films in the 3.8 wt% NaCl solution was measured before the polarisation experiments.

IV. Result and Discussion

The creation of high-performance coatings for the prevention of corrosion in structural materials has produced encouraging outcomes. By combining the benefits of high strength from Nano crystalline materials and high corrosion resistance from amorphous materials, the coatings were created utilising a novel approach of Nano crystalline and amorphous composite microstructures. Based on the phosphorus (P) content in the NiP alloy, the coatings' characterisation revealed unique microstructures. The coating showed a crystal structure when the P level was less than 5.5 weight percent. The coating revealed an amorphous and Nano crystalline composite structure in the P concentration range of 5.5 to 10.8wt%. The coating clearly had an amorphous structure when the P level was higher than 10.4wt%. As shown in figure 2 it contain structure reference as (a) P = 3.2 wt %; (b) P = 5.8 wt %; (c) P = 8 wt %; (d) P = 13.1 wt %.

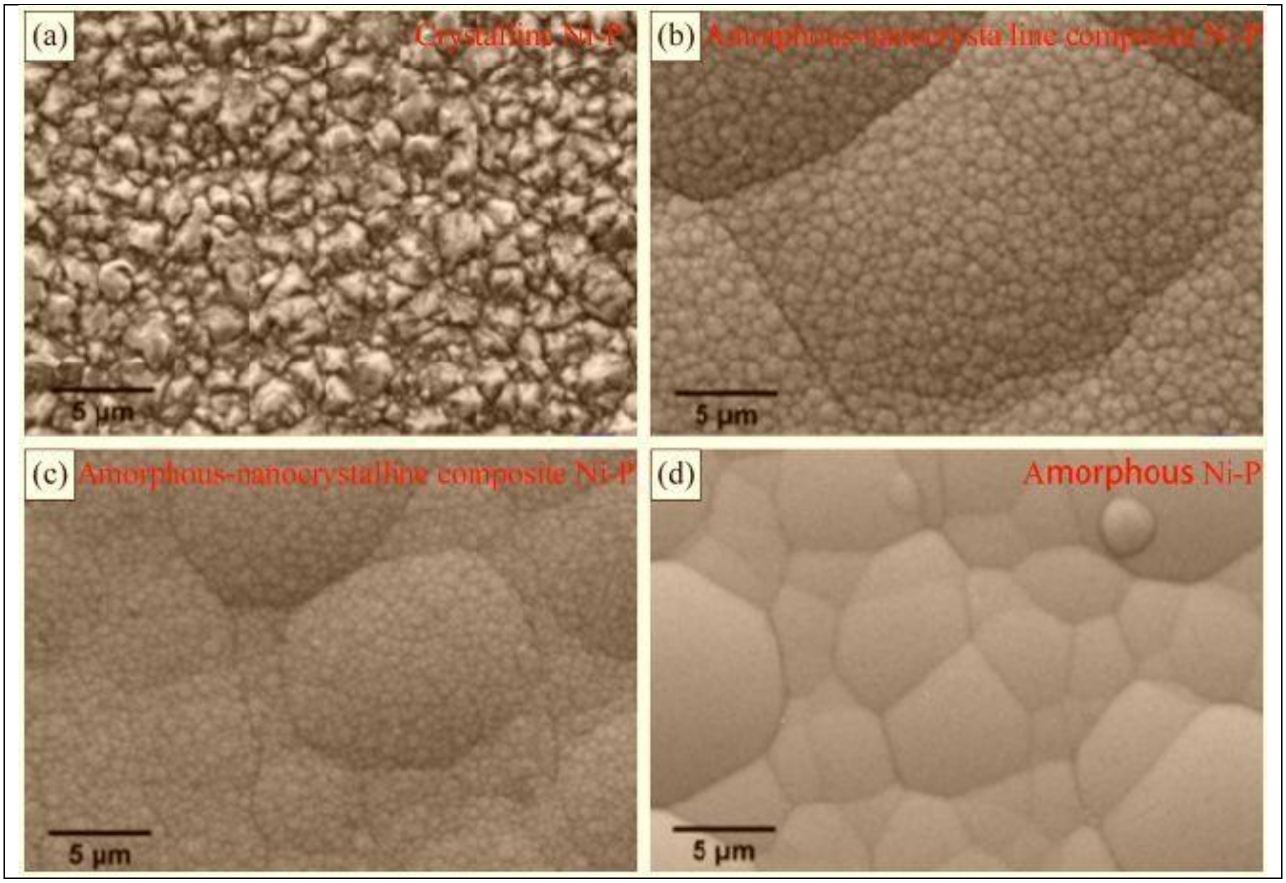

Figure 2: NiP coatings' surface morphology with various phosphorus concentrations

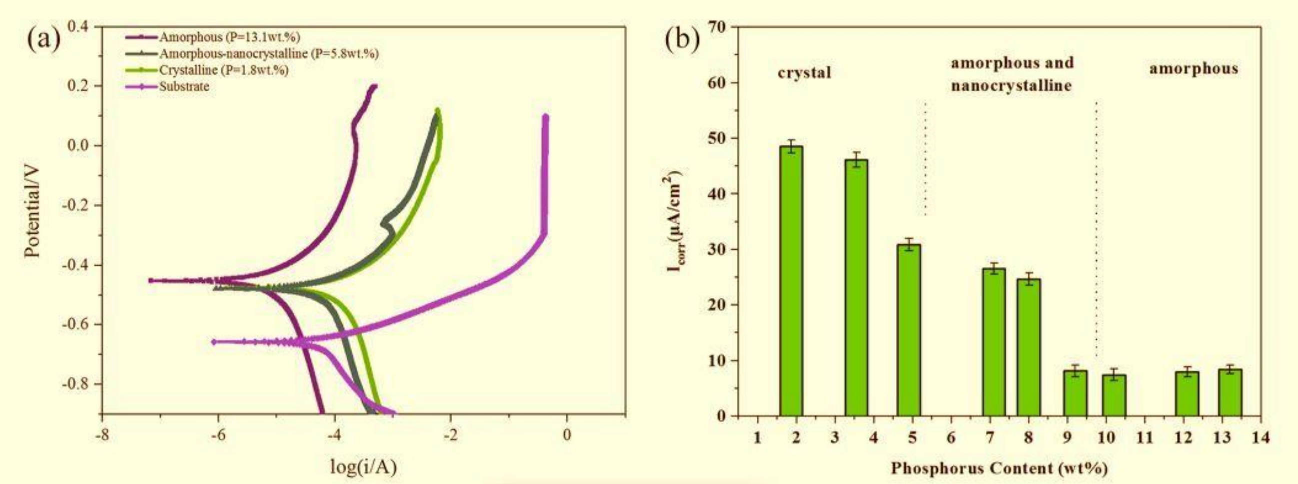

Figure 3: (a) Analysis of the polarisation curve and (b) self-corrosion current for various coating types at 0.1 MPa.

Due to their unique microstructures, the NiP coatings created for this investigation showed varied corrosion current density and corrosion potentials. While the crystal NiP coating demonstrated increased corrosion current density, the presence of an amorphous structure significantly improved corrosion resistance.

The amount and distribution of nanocrystalline inside the amorphous matrix phase largely determined how the NiP films corroded. The precise properties of the nanocrystalline phase were crucial in defining the coatings' overall corrosion resistance.

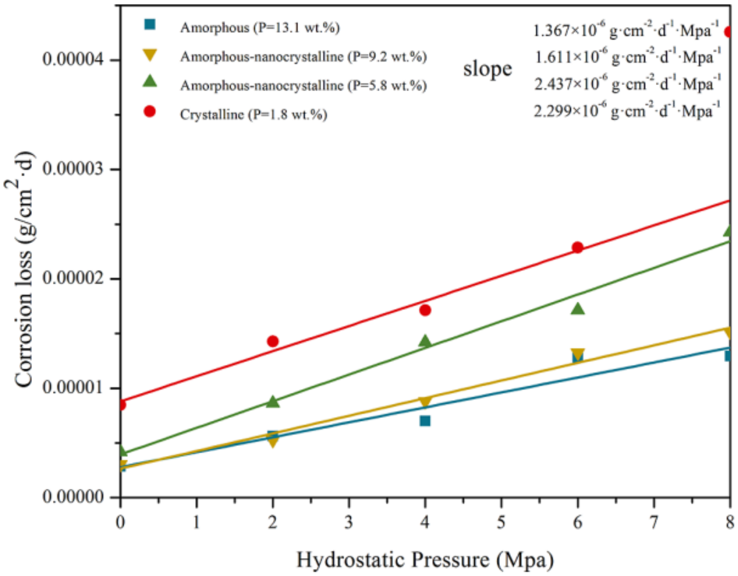

Figure 4: Graph showing the average acceleration caused by hydrostatic pressure on the coatings and Corrosion Rate

The outcomes of the high-pressure immersion test that was performed on the various coatings are shown in Figure 4. The impact of hydrostatic pressure on the pitting performance of X70 pipeline steel was examined in earlier investigations by Yang et al.15,16. These experiments' results showed that hydrostatic pressure significantly aided the beginning and development of pitting corrosion. Hydrostatic pressure was also found to facilitate other parts of the corrosion process.

The findings show that seawater's hydrostatic pressure has a considerable negative impact on the coatings' ability to resist corrosion. However, the detrimental impact of high hydrostatic pressure is greatly diminished as compared to the crystalline coating and amorphous-nanocrystalline coatings (P = 5.8 wt%). This decrease in adverse effects can be linked to the nanocrystalline coating's worse protection due to the existence of more grain boundaries. Conversely, when the amorphous region expands, the coating density rises and the porosity falls, lessening the harmful effects of high hydrostatic pressure. The crystalline coating shows the maximum corrosion loss at each hydrostatic pressure level; it is roughly twice as high as the amorphous coating. With an increase in phosphorus content, the corrosion loss for the amorphous-nanocrystalline coating reduces. These results underline how crucial the coating's microstructure and phosphorus concentration are in determining how well it resists corrosion under high hydrostatic pressure.

V. Conclusion and Future Directions

The findings showed that, in accordance with deeper seawater, the corrosion rate increased as hydrostatic pressure increased. The average acceleration effect of hydrostatic pressure on the corrosion rate throughout the range of 0.1 to 8 MPa was found to be 1.611 10-6 gcm-2d-1MPa-1 for the amorphous-nanocrystalline coatings with a phosphorus concentration of 9.2 wt%. These results highlight the significance of taking hydrostatic pressure into account when assessing the corrosion resistance of coatings. Under conditions of high hydrostatic pressure, the amorphous-nanocrystalline coatings showed promise corrosion resistance, but the crystalline coatings showed the highest rates of corrosion. This study offers insightful information for the creation of high-performance coatings for the prevention of corrosion in situations with variable hydrostatic pressures, which is especially important for structural materials.

The proportion of the amorphous region extends as the phosphorus level rises in the amorphous-nanocrystalline coating, increasing coating density and decreasing porosity. As a result, the harmful effects of excessive hydrostatic pressure are reduced. At different seawater depths, the amorphous-nanocrystalline coating's corrosion weight loss and seawater pressure acceleration rate (P = 9.2 wt%) are equivalent to those of the amorphous coating. The amorphous-nanocrystalline composite shows promise for the development of high-strength and long-lasting structural materials, according to prior findings on the wear resistance of the three coatings.

The research's next phase will concentrate on analysing the tribocorrosion characteristics of the three coatings at various hydrostatic pressures and potentials. This research attempts to gain understanding of the wear mechanisms that take place at various saltwater depths. In order to further progress the creation of high-performance coatings for structural materials and increase their strength and durability in demanding situations, it is necessary to thoroughly understand the behaviour of corrosion, wear, and tribology.

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