

# Effectiveness of PTFE-Based Nano-coatings in Improving Corrosion and Wear Resistance of Stainless Steel

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## Abstract

*Polytetrafluoroethylene (PTFE) has emerged as a highly effective material for enhancing the durability and performance of metal surfaces, particularly in environments requiring superior corrosion resistance and low friction. This study investigates the application of PTFE coatings on various metallic substrates, with a focus on stainless steel and carbon steel, to improve their corrosion resistance, wear protection, and tribological performance. Utilizing advanced deposition techniques such as sol-gel and plasma spray, PTFE was applied to metal surfaces, forming a robust barrier against corrosive environments. The study also explores the integration of titanium dioxide (TiO<sub>2</sub>) nanoparticles into PTFE coatings, creating a nanocomposite that enhances the antibacterial properties of stainless steel implants. Corrosion tests in 40% HCl revealed significant improvements in corrosion resistance, with PTFE-coated metals demonstrating reduced current density and enhanced surface integrity. Additionally, tribological tests showed a considerable reduction in friction coefficients, particularly in components such as bearings and spherical joints. Molecular dynamics simulations further elucidate the role of helix reversal defects in PTFE's phase behavior, contributing to its mechanical stability at elevated temperatures. The findings suggest that PTFE coatings, particularly when combined with TiO<sub>2</sub>, offer a promising solution for extending the lifespan of metallic components in harsh industrial and biomedical environments. This research presents a pathway for optimizing PTFE-based coatings for metallurgical applications, contributing to advancements in surface engineering technologies.*

**Keywords:** Polytetrafluoroethylene (PTFE), corrosion resistance, tribological performance, nanocomposites, surface engineering

## INTRODUCTION

In terms of high chemical inertness, good hydrophobicity, antifriction properties, self-lubrication properties, and high-temperature resistance, polytetrafluoroethylene (PTFE) is a class of polymers. PTFE has excellent non-stick properties, a relatively high melting temperature of 325°C, and is chemically inert. The rich phase behavior of polytetrafluoroethylene (PTFE), which is made up of an

organic helical chain structure, was created from a chemically simple polymer. Differential long-chain carbon-fluorine molecule orientations have been investigated under various conditions. Chain originated crystal morphology differences have been defined by X-ray studies on high temperature treated PTFE [1-2]. The Du Pont Company used the trade name Teflon™ for PTFE. Below 300°C, PTFE is an inert, stable, and non-hazardous substance. The low friction of PTFE has made it suitable for use in appliances acting beneath sliding parts, as well as in plain bearings, gears, slide plates, seals, gaskets, and bushings. As an

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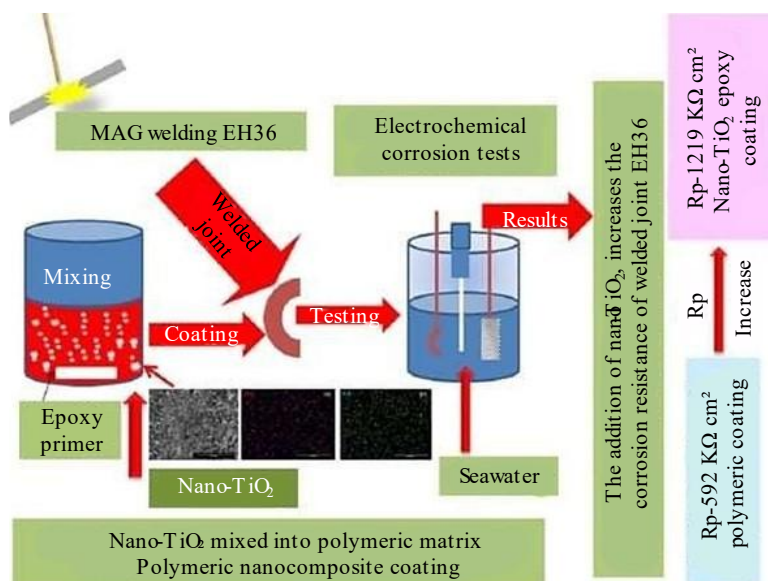
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engineering plastic, PTFE has low friction as well as chemical, high temperature, and weathering resistance. Tape, fabric, and tubing made of PTFE are available. TiO<sub>2</sub>-PTFE nanocomposite coatings with antibacterial properties have shielded 316 L stainless steel implants from bacterial contamination and corrosion.



**Figure 1.** Adding Nano-TiO<sub>2</sub> to polymeric nanocomposite coatings.

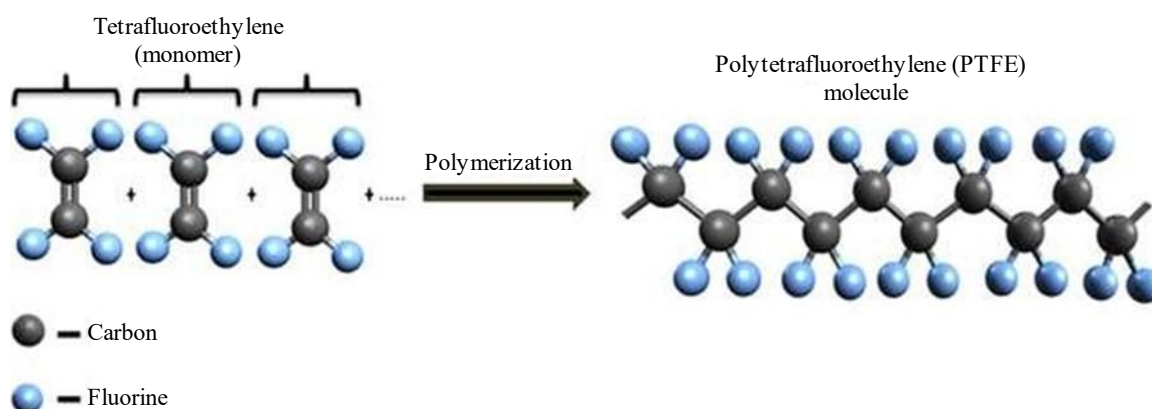
The diagram illustrates how adding Nano-TiO<sub>2</sub> to polymeric nanocomposite coatings can significantly improve the corrosion resistance of welded joints in EH36 steel. The process begins with mixing Nano-TiO<sub>2</sub> particles into an epoxy primer, creating a specialized coating. This coating is then applied to a welded joint of EH36 steel, which was joined using metal active gas (MAG) welding. Once applied, the coated sample undergoes electrochemical corrosion testing in seawater. This involves immersing the sample in the seawater and applying an electric current to measure how well the coating resists corrosion. The results show that the Nano-TiO<sub>2</sub>-enhanced epoxy coating offers much better protection against corrosion. Specifically, the polarization resistance ( $R_p$ ) increases from 592  $\text{k}\Omega\cdot\text{cm}^2$  with the standard epoxy coating to 1219  $\text{k}\Omega\cdot\text{cm}^2$  with the Nano-TiO<sub>2</sub> epoxy nanocomposite coating. Figure 1. Overall, the addition of Nano-TiO<sub>2</sub> significantly boosts the coating's barrier properties, providing superior resistance to corrosive environments, especially in marine settings. This approach shows great promise for extending the lifespan and durability of welded steel structures exposed to harsh conditions.

The functionalized stainless-steel substrate with catechol groups has been coated with the descriptive issued scheme, and the evaluated platform has since been used for secondary reactions to deposit TiO<sub>2</sub> sols. Thus, TiO<sub>2</sub>-PTFE coatings were made using the simple sol-gel method. While anti-corrosion properties have been evaluated using the electrochemical method, anti-bacterial and anti-adhesion efficiencies of coatings have been estimated after tests of exposure from Gram-negative (*Escherichia coli*) and Gram-positive (*Staphylococcus aureus*) bacterial strains [3]. Radiofrequency plasma spray and atmosphere plasma spray were used to apply a PTFE coat to mild steel. According to evaluation results, the subjected scheme produced a friction coefficient that was twice as high under atmospheric plasma treatment conditions as it was when PTFE coating was applied to substrates subjected to low-pressure RF plasma treatment. Steel now has a coat to help prevent wear on exposed appliances in moving machinery. Such parts, such as machine components such as bearings, shafts, gears, and bolts, have improved tribological properties thanks to PTFE coatings. Studies in tribology have been done on either the subsidization of solid lubricant, polymer, or both. According to logical scripture, PTFE surfaces with good wear and corrosion resistance, self-lubrication, low noise, and

low-cost relevance are appropriate for use in performance evaluation. Additional schemes to interpret the properties of joints after coat application on balls have been subjected by the decisive consideration of friction and clearance in spherical joints [4]. It has been stated that the kinematic accuracy of mechanisms with joints is important for interpreting joint clearances.

**Purpose of the Review and Scope:** This review aims to critically examine and synthesize current advancements in polytetrafluoroethylene (PTFE) coatings, particularly in the context of material science and engineering applications. PTFE is widely recognized for its extraordinary chemical resistance, low friction, hydrophobicity, and high-temperature tolerance. Its diverse applications range from corrosion protection to enhancing tribological properties in mechanical systems. However, with evolving material needs, the use of PTFE in conjunction with other materials, such as titanium dioxide (TiO<sub>2</sub>), has opened up new research areas in nanocomposites, biocompatibility, and environmental resistance.

The review will explore the molecular dynamics of PTFE, including helix reversals and phase transitions, providing insight into how these structural changes impact its overall mechanical and physical properties. Furthermore, it will detail the various coating techniques utilized for PTFE, such as plasma spraying and sol-gel methods, and their implications for performance in different engineering environments.



**Figure 2.** Molecular Structure and Dynamics of PTFE.

This section will delve into the unique molecular structure of PTFE, focusing on its helical carbon-fluorine backbone. You'll explore how this molecular arrangement contributes to its chemical inertness and thermal stability. Topics like helix reversals and rotational disorder within the PTFE chains will be discussed, emphasizing how these structural behaviors affect the polymer's phase transitions and mechanical properties. Figure 2 Additionally, the relationship between PTFE's crystallinity and its performance under different temperatures and environmental conditions will be examined.

At the core of PTFE's functionality is its linear chain structure, consisting of repeating units of tetrafluoroethylene ( $-\text{CF}_2-\text{CF}_2-$ )<sub>n</sub>. Each carbon atom is bonded to two fluorine atoms, forming a highly stable and robust carbon-fluorine bond, which gives PTFE its outstanding chemical inertness and resistance to extreme temperatures.

### Carbon-Fluorine Bond: Strength and Stability

The carbon-fluorine bond is one of the strongest single bonds in organic chemistry, with a bond energy of around 485 kJ/mol. This high bond strength arises from the small atomic radius of fluorine and its strong electronegativity, which draws electron density towards itself, reinforcing the bond. This contributes to PTFE's remarkable resistance to acids, bases, solvents, and even highly corrosive chemicals like hydrofluoric acid. The electron cloud shielding created by fluorine atoms also prevents reactions with other chemicals, making PTFE virtually non-reactive under most conditions.

### **Helical Molecular Structure**

The molecular chains of PTFE adopt a helical conformation, which distinguishes it from many other polymers. The fluorine atoms, positioned along the periphery of the helix, form a protective barrier around the carbon backbone. This helical configuration contributes to PTFE's low surface energy, resulting in its well-known anti-adhesive properties, which make it highly effective as a non-stick coating. The helical arrangement also allows PTFE to maintain structural stability even under mechanical stress, further enhancing its wear resistance and durability in challenging environments [5].

### **Crystallinity and Phase Transitions**

PTFE exhibits semi-crystalline behavior, with regions of crystalline and amorphous phases. In its crystalline form, PTFE has a high degree of order, which is responsible for its stiffness and rigidity. The degree of crystallinity is a key factor influencing PTFE's mechanical properties, such as its tensile strength and elongation at break. As temperature increases, PTFE undergoes a series of phase transitions. At approximately 19°C, PTFE transitions from a triclinic to hexagonal crystal structure, which is associated with the alignment of its molecular chains. This transition is known as the "melting of the helical structure" and is critical for PTFE's thermal expansion and flexibility at higher temperatures.

### **Helix Reversal and Mechanical Behavior**

A distinctive feature of PTFE's molecular dynamics is helix reversal, a phenomenon where the direction of the helical twist in the polymer chains changes. This occurs under mechanical or thermal stress and has significant implications for PTFE's mechanical properties. Helix reversal can influence PTFE's flexibility, impacting how it responds to external forces, such as compression or tension. When PTFE experiences high levels of stress, localized helix reversals may lead to changes in its crystallinity, which can alter its wear resistance and durability [6].

Helix reversal also plays a role in PTFE's self-lubricating properties, as the molecular rearrangements reduce internal friction between chains, facilitating smoother movement over surfaces. This is why PTFE is highly valued in applications where low friction and wear resistance are critical, such as in sliding bearings, seals, and gaskets.

### **Molecular Weight and Chain Length**

The molecular weight of PTFE can vary widely, and this variation significantly affects its processing and performance characteristics. High molecular weight PTFE has longer polymer chains, which contribute to its high melting point and exceptional mechanical strength. However, this also makes it more difficult to process through conventional methods like injection molding or extrusion. To address this, low-molecular-weight PTFE is often used in applications requiring easier processing, such as coatings or lubricants, where extreme mechanical strength is not the primary concern.

### **Role of Molecular Dynamics in PTFE Applications**

The unique molecular structure of PTFE has a direct influence on its application in various industries. For instance, in the aerospace sector, the combination of low friction, high thermal resistance, and chemical inertness makes PTFE an ideal material for coating parts that experience extreme environmental conditions. In electronics, the stability of the carbon-fluorine bond at high frequencies allows PTFE to be used as an insulating material in high-frequency cables and components.

### **Deposition Techniques for PTFE Coatings**

Here, you will discuss various methods used to apply PTFE coatings to different substrates. Techniques such as plasma spraying, dip-coating, and sol-gel methods will be explored. Each method's benefits and limitations will be highlighted, along with their specific applications in industries such as aerospace, automotive, and biomedical engineering. You can also touch on

emerging deposition technologies that improve coating adhesion, uniformity, and performance, particularly in challenging environments.

### Nano-Coatings and Composite Materials: PTFE-TiO<sub>2</sub> Innovations

This section explores the integration of PTFE with other materials, such as titanium dioxide (TiO<sub>2</sub>), to create advanced nanocomposite coatings. The combination of PTFE's anti-friction properties with TiO<sub>2</sub>'s antibacterial and corrosion resistance makes these coatings particularly useful for medical implants and high-performance engineering materials. The section will discuss how these composites are created, their unique properties, and potential applications, with a focus on the synergy between PTFE and nanomaterials for enhanced functionality.

### Corrosion Resistance and PTFE Coatings

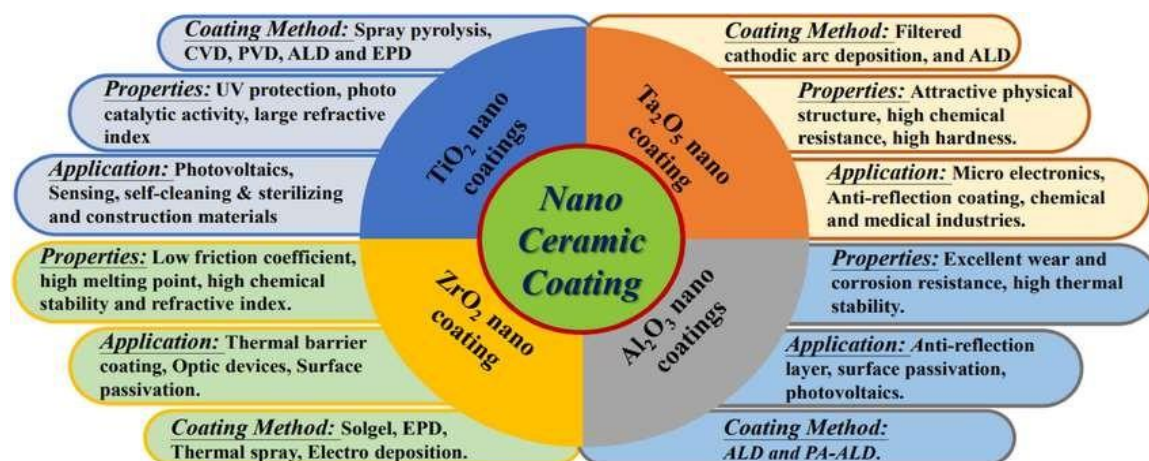
Here, you will explore the application of PTFE as a corrosion inhibitor. PTFE's hydrophobicity and chemical resistance make it an ideal coating for metals like stainless steel, often exposed to harsh environments. The section will focus on PTFE's role in protecting metals from acid, alkaline, and saline conditions, drawing on specific studies such as its performance in HCl environments. Comparative analysis of PTFE with other corrosion-resistant coatings will also be discussed, highlighting its advantages in terms of durability and performance.

### Tribological Performance After PTFE Coating

This section focuses on PTFE's role in reducing friction and wear in mechanical systems. PTFE coatings are widely used in applications requiring high wear resistance, such as gears, bearings, and joints. You'll discuss the tribological benefits of PTFE, including its ability to lower friction coefficients and reduce surface wear. Studies on PTFE-coated components in dynamic environments, like automotive and aerospace systems, will be reviewed to demonstrate how PTFE enhances longevity and efficiency [7-8].

### Nano Coat on Stainless Steel

Advanced titanium dioxide-polytetrafluorethylene (TiO<sub>2</sub>-PTFE) nanocomposite coatings on stainless steel surfaces with antibacterial and anti-corrosion properties were described. The use of biomedical metallic implants has frequently failed due to bacterial infection and corrosion. Applying a sol-gel simple two-step dip coat of TiO<sub>2</sub>-PTFE nanocomposite on the stainless-steel substrate has enabled success against bacteria and corrosion. Using a methodical application, a bio-inspired Polydopamine (PDA) sub-layer was formed on a stainless-steel substrate. This improved the adhesion and reactivity of the ensuing TiO<sub>2</sub>-PTFE coat, which was uniformly co-deposited onto the PDA sub-layer. Based on the components of both PTFE and TiO<sub>2</sub>, significant influence on the surface energy



**Figure 3.** Coating methods, properties, and applications of TiO<sub>2</sub>, Ta<sub>2</sub>O<sub>5</sub>, Al<sub>2</sub>O<sub>3</sub>, and ZrO<sub>2</sub> nano ceramic coatings.

of TiO<sub>2</sub>-PTFE coating has been studied. With a total surface energy of 26 mJ/m<sup>2</sup>, a corresponding access of coat has been achieved, exhibiting minimal bacterial adhesion against both Gram-negative *Escherichia coli* WT F1693 and Gram-positive *Staphylococcus aureus* F1557. TiO<sub>2</sub>-PTFE coat has demonstrated improved corrosion resistance in bodily fluids when compared to either TiO<sub>2</sub> coat or PTFE coat as a result of the synergisms between the two materials. It has been suggested that the TiO<sub>2</sub>-PTFE coating is biocompatible with fibroblast cells in culture, which supports the use of metallic implants. Despite the fact that deficiencies have been studied as bacteria adhering to implant surfaces, bacteria now become embedded in a dense extracellular matrix to ward off host defence mechanisms like antibiotic penetration [9-10].

### Corrosion Inhibitor

Stainless steel (SS) are used frequently in a variety of engineering applications due to their excellent corrosion resistance in various media and fine mechanical properties. Because 316L stainless steel requires a hard coat to withstand wear and corrosion, it exhibits poor corrosion behavior in HCL [11]. Polytetrafluoroethylene (PTFE) has recommended using the spin coating method to coat the 316L SS.

Following that, a 40% HCl electrochemical corrosion test was used to modify corrosion resistance in acidic media containing HCL, and potentiodynamic polarization curves were created at room temperature for comparative analysis [12]. While compositional analysis was carried out using energy dispersive x-ray spectroscopy (EDX), scanning electron microscopy (SEM) was used to investigate morphological improvements from specimens before and after corrosion tests. Since the polymer has passivation to current flow, the thickness of the coating reduces the corrosion current density in HCL media, thereby improving the corrosion resistance of the PTFE coating [13].

### CONCLUSION

in summary, this study highlights the significant advancements in utilizing PTFE-based coatings to enhance the corrosion resistance and wear properties of stainless steel and other metallic substrates. Polytetrafluoroethylene (PTFE) has proven to be an exceptional material due to its chemical inertness, low friction, and high-temperature stability. When applied to metal surfaces, PTFE coatings form a protective barrier that significantly improves resistance to corrosion, especially in harsh environments such as acidic or saline conditions. The integration of titanium dioxide (TiO<sub>2</sub>) nanoparticles with PTFE to create nanocomposite coatings has further expanded the scope of these materials. The TiO<sub>2</sub>-PTFE nanocomposites not only enhance the corrosion resistance but also impart antibacterial properties, making them highly suitable for biomedical applications, such as implants that need to resist bacterial contamination and corrosion. This dual functionality of the coatings ensures better protection and longevity of metallic components used in both industrial and medical fields.

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