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Vanadium Pentoxide Coatings to Enhance Mechanical Properties of Metallic Substrates at High-Stress Conditions

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Abstract

In this work, vanadium pentoxide coatings were applied to metallic substrates and their effects on the overall mechanical behaviors of these substrates were determined and analyzed. The V_2O_5 coatings offer remarkable advantages in energy storage, smart windows, corrosion protection, sensing, catalysis, and thermoelectric applications. Various preparation methods, such as PVD, CVD, sol-gel, and electrochemical deposition, allow tailored coatings for specific industrial needs. While challenges remain, ongoing research promises further improvements, expanding the role of V_2O_5 coatings in next-generation engineering solutions. As industries seek sustainable and high-performance materials, V_2O_5 coatings will continue to play a pivotal role in advancing technology.

Keywords: Magnetron co-sputtering; Reactive sputtering; Nickel ferrite; Nanostructures

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1. Introduction

Vanadium pentoxide (V_2O_5) is a transition metal oxide with unique electrochemical, optical, and catalytic properties, making it highly valuable in various engineering and industrial applications. V_2O_5 coatings are widely used in energy storage, corrosion protection, smart windows, sensors, and catalysis due to their excellent redox behavior, layered structure, and thermal stability. This article explores the preparation methods of V_2O_5 coatings and their advantages in different industrial and engineering applications [1-5].

Several techniques are employed to deposit V_2O_5 coatings, each offering distinct advantages in terms of film quality, thickness control, and scalability. The most common methods include physical vapor deposition (PVD) techniques, such as sputtering and evaporation, are widely used to produce high-purity V_2O_5 coatings with excellent adhesion and uniformity [6,7]. In magnetron sputtering, a high-energy plasma bombards a vanadium target in an oxygen-rich environment, forming a dense and uniform V_2O_5 film. This method allows precise control over stoichiometry and thickness [8,9]. In thermal evaporation, vanadium oxide is evaporated in a vacuum and condensed onto a substrate. Post-deposition annealing in oxygen converts it into V_2O_5. The advantages of PVD techniques can be seen in high film purity and density, excellent control over film thickness and composition, and suitable for large-scale industrial production [10,11]. Chemical vapor deposition (CVD) techniques are also used to prepare V_2O_5 thin films. They involves the reaction of volatile vanadium precursors (e.g., vanadium oxytrichloride, $VOCl_3$) with oxygen at elevated temperatures to form V_2O_5 coatings. Plasma-enhanced CVD (PECVD) uses plasma to enhance deposition rates at lower temperatures, making it suitable for temperature-sensitive substrates. The advantages of CVD are described by the conformal coatings on complex geometries, high deposition rates, and good adhesion and uniformity [12,13]. Sol-gel deposition method involves dissolving vanadium precursors (e.g., vanadium alkoxides) in a solvent, followed by hydrolysis and condensation to form a gel. The gel is then spin-coated or dip-coated onto a substrate and annealed to form crystalline V_2O_5. This method show some advantages such as low-cost and simple process, tunable composition and porosity, and suitable for large-area coatings [14,15]. The electrochemical deposition method involves the electrochemical reduction of vanadium species (e.g., V^{5+}) from an electrolyte onto a conductive substrate. The deposited film is then oxidized to form V_2O_5. Using the electrochemical deposition, room-temperature processing, precise control over film thickness, and suitable coatings for flexible substrates can be achieved. In spray pyrolysis, a precursor solution containing vanadium salts is sprayed onto a heated substrate, where thermal decomposition forms V_2O_5 films. The advantages of spray pyrolysis are observed in scalability for industrial applications, low equipment cost, and suitability for large-area coatings [16,17].

V_2O_5 coatings are advantageous in engineering and industrial applications as they exhibit exceptional properties that make them suitable for a wide range of applications. V_2O_5 is a promising cathode material for lithium-ion batteries (LIBs) and supercapacitors due to its high theoretical capacity (~294 mAh/g) and layered structure, which allows efficient Li^+ intercalation. They show high energy density and cycling stability, fast charge-discharge kinetics, and potential for flexible and thin-film batteries [18]. V_2O_5 coatings exhibit electrochromic behavior, changing color with applied voltage, making them ideal for energy-efficient smart windows. They reduces building energy consumption by modulating light and heat transmission, show long-term stability and durability, and they are compatible with flexible and transparent substrates. V_2O_5 coatings act as protective barriers against oxidation and corrosion in harsh environments, particularly for steel and aluminum alloys. These coatings are chemically inert and resistant to oxidation, enhancing the lifespan of industrial components, and can be combined with other coatings (e.g., polymers) for improved performance [4,8]. V_2O_5 is highly sensitive to gases such as NH_3, NO_2, and volatile organic compounds (VOCs), making it useful in environmental monitoring and industrial safety sensors. These sensors show high sensitivity and selectivity, fast response and recovery times, and operate at relatively low temperatures. V_2O_5 serves as an effective catalyst in oxidation reactions, such as the selective catalytic reduction (SCR) of NO_x in automotive exhaust systems. They show high catalytic activity and thermal stability, promotes environmentally friendly chemical processes, and can be integrated into photocatalytic systems for pollutant degradation [2,11]. V_2O_5 exhibits good thermoelectric properties, converting waste heat into electricity in industrial processes. The advantages can be seen in enhancement in energy efficiency in power plants and manufacturing, stability at high temperatures, and they can be combined with other oxides for improved performance [19].

Despite their advantages, V_2O_5 coatings face some challenges. First, poor electrical conductivity as doping with metals (e.g., W, Mo) or carbon can enhance conductivity. Second, mechanical brittleness as the composite coatings with polymers or other oxides improve flexibility. Third, the long-term stability as research is ongoing to enhance durability under harsh conditions. Future developments may include nanostructured V_2O_5 coatings for enhanced surface area and reactivity, hybrid coatings combining V_2O_5 with graphene or conductive polymers, and AI-driven optimization of deposition parameters for tailored properties [7,20].

In this work, vanadium pentoxide coatings were applied to metallic substrates and their effects on the overall mechanical behaviors of these substrates were determined and analyzed.

2. Experiment

Figure (1) shows the experimental setup of the electrochemical deposition method used in this work. Iron (Fe), copper (Cu), aluminum (Al), and zinc (Zn) substrates were polished to a mirror finish and cleaned ultrasonically in acetone and ethanol to remove surface contaminants. An acid pickling step (HCl for Fe, HNO_3 for Cu, NaOH for Al, and H_2SO_4 for Zn) was used to enhance coating adhesion. To prepare the electrolyte, a solution of ammonium metavanadate (NH_4VO_3) in distilled water with a supporting electrolyte (Na_2SO_4) was used. The deposition parameters are voltage, dc potential (1–3 V), current density 1–10 mA/cm² to control coating thickness, and deposition time (10 min, 110 min, and 160 min) to achieve 1 µm, 10 µm, and 100 µm thicknesses, respectively. A post-deposition treatment was performed as the coated samples were annealed at 300–400°C in air to convert vanadium oxide phases into crystalline V_2O_5.

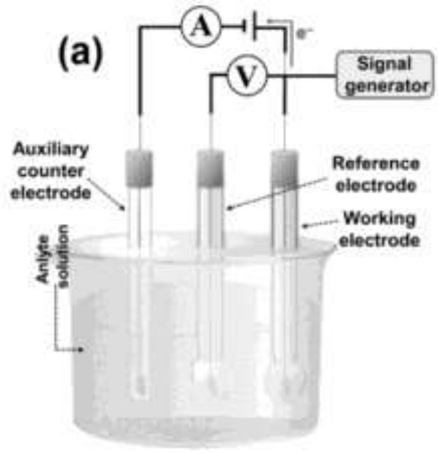

Fig. (1) The experimental setup of the electrochemical deposition method used in this work

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Characterization included thickness measurement by profilometry and cross-sectional SEM, and mechanical testing, mainly, microhardness using Vickers hardness tester, wear resistance using pin-on-disk tribometer, and adhesion strength by scratch test and ASTM D3359 tape test.

3. Results and Discussion

Figure (2) illustrates the effect of coating thickness on the microhardness of materials coated with V_2O_5. A thin 1 µm coating yields only a modest hardness increase (~7.5%), as the layer is too thin to offer substantial mechanical reinforcement. At 10 µm, hardness improves significantly (~25%), reflecting enhanced load-bearing capacity due to better surface coverage. The 100 µm coating achieves the highest hardness gain (~45%), demonstrating excellent resistance to deformation. However, such thick coatings may introduce internal stresses, potentially leading to microcracking or delamination. Therefore, while thicker coatings improve hardness, optimal thickness must balance performance with structural integrity and reliability.

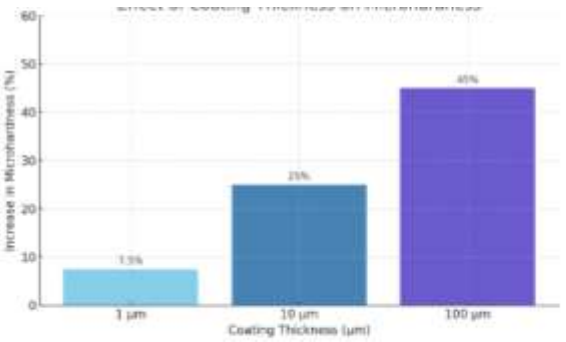

Fig. (2) The variation of metallic substrate microhardness with V_2O_5 coating thickness

Figure (3) demonstrates the impact of coating thickness on wear resistance. A 1 µm coating provides only a modest wear rate reduction (~15%), likely due to insufficient coverage and limited durability under friction. At 10 µm, wear resistance is maximized (~50% reduction), representing the optimal balance between hardness and toughness, where the coating can effectively protect the substrate without becoming brittle. Although the 100 µm coating still offers high wear resistance (~45% reduction), it may suffer from internal stresses and increased brittleness, leading to potential delamination under heavy mechanical loads. Therefore, 10 µm is identified as the most efficient thickness for wear protection.

Figure (4) illustrates how coating thickness influences adhesion strength based on ASTM classifications. A 1 µm coating exhibits excellent adhesion (Class 5B), attributed to low internal stress and strong interfacial bonding. At 10 µm, adhesion slightly decreases to Class 4B, with minor edge delamination likely due to moderate residual stresses developing within the thicker layer. The 100 µm coating shows poor adhesion (Class 3B or lower), primarily caused by high internal stresses and thermal mismatch, which weaken the bond to the substrate. This analysis highlights that as coating thickness increases, adhesion strength typically declines, emphasizing the need to optimize thickness for structural reliability.

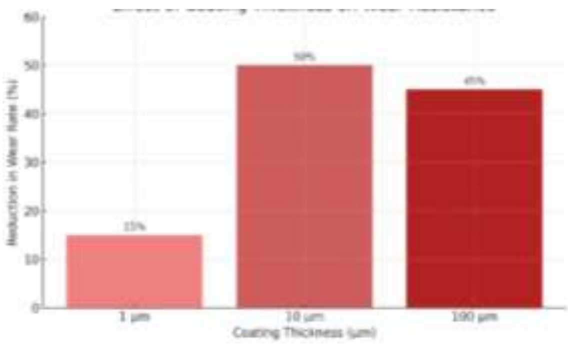

Fig. (3) The variation of wear rate of metallic substrate with V_2O_5 coating thickness

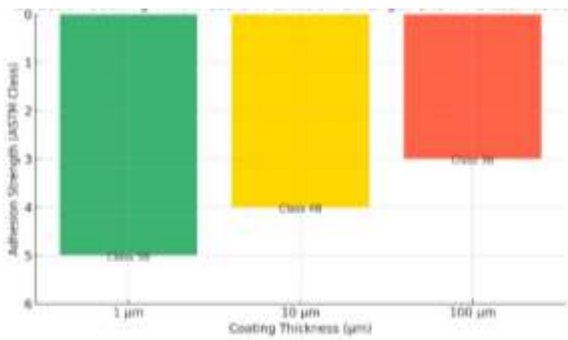

Fig. (4) The variation of adhesion strength of V_2O_5 coatings on metallic substrate with coating thickness

4. Conclusion

V_2O_5 coatings offer remarkable advantages in energy storage, smart windows, corrosion protection, sensing, catalysis, and thermoelectric applications. Various preparation methods, such as PVD, CVD, sol-gel, and electrochemical deposition, allow tailored coatings for specific industrial needs. While challenges remain, ongoing research promises further improvements, expanding the role of V_2O_5 coatings in next-generation engineering solutions. As industries seek sustainable and high-performance materials, V_2O_5 coatings will continue to play a pivotal role in advancing technology.

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