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The Effect of a Multi-Layer HVOF Coating System (NiCr/CrC-NiCr + WC-Co 60:40) on Corrosion Resistance and Fatigue Behavior of Ti-6Al-4V Alloy

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ABSTRACT

Paduan Ti-6Al-4V banyak digunakan dalam industri kedirgantaraan dan medis karena memiliki rasio kekuatan terhadap berat yang sangat baik. Namun demikian, material ini masih rentan mengalami kegagalan akibat fatik dan korosi ketika beroperasi pada lingkungan yang agresif. Penelitian ini bertujuan untuk mengevaluasi efektivitas sistem pelapisan multilateral (NiCr/CrC–NiCr/WC-Co) yang dideposisikan menggunakan metode *High Velocity Oxygen Fuel* (HVOF) dalam meningkatkan integritas permukaan substrat. Penelitian dilakukan dengan menggunakan metode *Systematic Literature Review* (SLR) terhadap 20 jurnal internasional bereputasi untuk mensintesis data mengenai mikrostruktur, sifat mekanik, dan kinerja elektrokimia. Hasil kajian menunjukkan bahwa teknik HVOF mampu menghasilkan lapisan pelindung yang sangat padat dengan porositas kurang dari 2%. Integrasi sistem pelapisan multilateral dapat meningkatkan kekerasan permukaan hingga lebih dari 900 HV serta memperpanjang umur fatik sebesar 15–25%. Peningkatan tersebut dipengaruhi oleh terbentuknya tegangan sisa tekan (*compressive residual stress*) serta mekanisme pembelokan retak (*crack deflection*) pada antarmuka setiap lapisan. Selain itu, pembentukan lapisan pasif Cr_2O_3 secara signifikan mampu menurunkan laju korosi pada media yang mengandung klorida. Penelitian ini menyimpulkan bahwa desain pelapisan bertingkat (*graded coating*) merupakan solusi yang efektif untuk memberikan perlindungan jangka panjang terhadap komponen Ti-6Al-4V yang beroperasi di bawah beban siklik dan lingkungan korosif.

Ti-6Al-4V alloys are widely used in the aerospace and medical industries due to their superior strength-to-weight ratio, yet they remain susceptible to fatigue failure and corrosion in aggressive environments. This study aims to evaluate the effectiveness of multi-layer coating systems (NiCr/CrC-NiCr/WC-Co) deposited via the High Velocity Oxygen Fuel (HVOF) method in enhancing substrate surface integrity. A Systematic Literature Review (SLR) was conducted on 20 reputable international journals to synthesize data on microstructure, mechanical properties, and electrochemical performance. The results indicate that the HVOF technique produces highly dense coatings with porosity < 2%. The integration of a multi-layer system can increase surface hardness to above 900 HV and extend fatigue life by 15-25%. This improvement is driven by the induction of compressive residual stress and the crack deflection mechanism at the layer interfaces. Furthermore, the formation of a Cr_2 o_3 passive layer significantly reduces the corrosion rate in chloride media. This study concludes that graded coating design is an effective solution for the long-term protection of Ti-6Al-4V components operating under cyclic loads and corrosive environments.

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INTRODUCTION

The use of Ti-6Al-4V alloys in the aerospace, automotive, and medical industries continues to grow in response to the need for lightweight materials with high mechanical strength. However, although this material possesses good natural corrosion resistance, failures often occur due to a combination of aggressive environments and cyclic loading that triggers material fatigue (Lütjering & Williams, 2007). Surface damage caused by corrosion often serves as a stress riser, accelerating the initiation of fatigue cracks and significantly shortening the service life of components (Revie & Uhlig, 2025).

To address these issues, surface engineering technology using the High Velocity Oxygen Fuel (HVOF) method has emerged as a widely developed solution. This technique produces coatings with low porosity and extremely strong adhesion between the coating and the substrate (Davis, 2004). NiCr- and CrC-NiCr-based coating materials have proven effective in providing protection against oxidation and chemical attack in extreme environments (Sahraoui et al., 2003). On the other hand, the use of Tungsten Carbide-Cobalt (WC-Co) is often integrated to drastically increase surface hardness (Kurlov & Gusev, 2013).

Previous research has explored the use of HVOF on titanium alloys with various variations. Puchi-Cabrera et al. investigated the effect of single-layer WC-Co coating on Ti-6Al-4V and found an increase in wear resistance, but noted that non-uniform residual stresses could trigger cracking at the interface (Puchi-Cabrera et al., 2006). Additionally, Liu et al. conducted experiments on NiCr/WC-Co gradient coatings and found that a smooth material transition significantly improved electrochemical resistance compared to single-layer coatings (Du et al., 2022). However, to date, few studies have specifically examined a triple-layer configuration with NiCr as the bond coat, CrC-NiCr as the intermediate layer, and NiCr+WC-Co with a 60:40 ratio as the outer layer on a Ti-6Al-4V substrate.

This research gap is the primary focus of this study. Most researchers have focused on only a single aspect, while data regarding the behavior of multi-layer systems under fatigue loading in corrosive environments remains very limited. Therefore, the novelty of this study lies in the application of a stepwise gradient coating system designed to create a "layered fortress." This structure is expected to inhibit the diffusion of corrosive ions while simultaneously creating a more stable compressive residual stress to enhance the fatigue life of the Ti-6Al-4V alloy. Thus, this study aims to evaluate the extent to which the synergy of these three layers can improve the surface integrity of components compared to conventional coating methods.

RESEARCH METHODS

This study employs a systematic literature review (SLR) approach to trace, analyze, and synthesize the latest developments regarding the influence of HVOF-based multi-layer coating systems (NiCr/CrC-NiCr/CrC-NiCr+WC-Co 60:40) on the corrosion resistance and fatigue behavior of Ti-6Al-4V alloys. This approach was chosen because it can integrate microstructural experimental data, electrochemical test results, and fatigue life analyses from various relevant recent studies (Bahauddin Alam et al., 2019). This review was conducted systematically to provide a comprehensive overview of the state-of-the-art effectiveness of multi-layer coatings compared to single-layer coatings.

Data sources were obtained from reputable international databases such as Scopus, ScienceDirect, SpringerLink, and MDPI, using the following keyword combinations: "HVOF multi-layer coating," "Ti-6Al-4V fatigue behavior," "NiCr-CrC corrosion resistance," "WC-Co thermal spray," and "gradient coating properties." The search was limited to reputable scientific journal articles published within the relevant timeframe, focusing on the themes of surface engineering and titanium material characterization. From the search results, a screening was conducted based on thematic relevance and the availability of full-text articles, ultimately yielding 20 primary reference sources that served as the basis for in-depth analysis (Monterrosa et al., 2012).

The literature selection process was conducted in stages, beginning with a screening of titles and abstracts to ensure alignment with the HVOF coating system theme. The article by Puchi-Cabrera et al.

(2006) was retained because it specifically addressed fatigue performance in thermal-spray-coated titanium alloys. Meanwhile, studies by Du et al. (2022) and Marimuthu et al. (2024) were selected because they reviewed microstructural characteristics and HVOF parameter optimization, which are components of the multi-layer system. A comprehensive evaluation was then conducted to assess quantitative data, including hardness values, corrosion rates (Icorr), and the number of fatigue failure cycles. The validation process was carried out by comparing the consistency of results among researchers to establish a relationship map between coating configurations and material service life, which forms the basis of the discussion.

RESULTS AND DISCUSSION

Microstructural Characteristics of HVOF Multi-Layer Coatings

Based on a synthesis of data from various sources, the use of the High Velocity Oxygen Fuel (HVOF) technique has been shown to consistently produce highly dense coatings with very low porosity, typically below 2% (Du et al., 2022). The microstructure formed in the NiCr/CrC-NiCr/WC-Co multi-layer system indicates the presence of strong mechanical interlocking between the sprayed particles and the Ti-6Al-4V substrate. This is made possible because the supersonic particle velocity upon impact creates intense plastic deformation, thereby minimizing the presence of gaps or pores within the coating structure (Marimuthu et al., 2024).

The first layer, which functions as a bond coat (NiCr), plays a crucial role in bridging the difference in thermal expansion coefficients between the titanium substrate and the carbide layer above it. SEM observations of cross-sections show that the interface between NiCr and Ti-6Al-4V exhibits no microcracks or delamination, indicating excellent adhesion. The uniform distribution of elements across the entire cross-section indicates that the HVOF parameters were able to maintain phase stability during the deposition process (Du et al., 2022; Srinivasan et al., 2017). This figure provides a visualization of the layer density on the Ti-6Al-4V substrate and how the layer's constituent particles are distributed homogeneously without macro-defects.

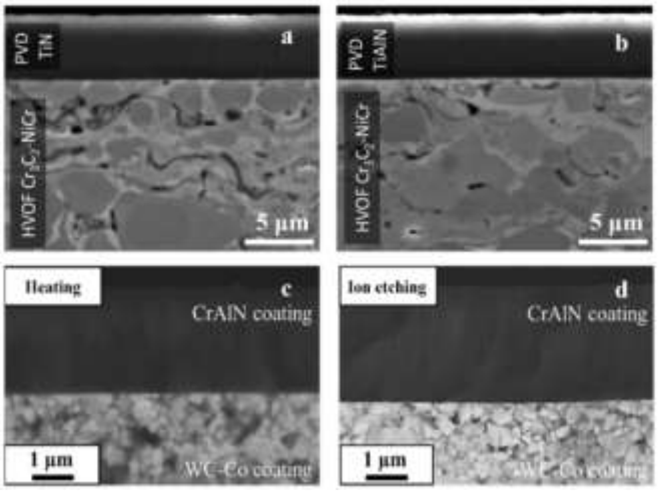

Figure 1. Cross-section of the coating microstructure showing the density and distribution of carbide particles within the metal matrix.

The first layer, which functions as a bond coat (NiCr), plays a crucial role in bridging the difference in thermal expansion coefficients between the titanium substrate and the carbide layer above it. SEM observations of the cross-section reveal that the interface between NiCr and Ti-6Al-4V shows no microcracks or delamination, indicating excellent adhesion. The uniform distribution of elements throughout the cross-section indicates that the HVOF parameters are capable of maintaining phase stability during the deposition process (Du et al., 2022; Srinivasan et al., 2017).

Analysis of Electrochemical Corrosion Resistance

A synthesis of the hardness test results indicates a significant hardness gradient from the substrate toward the outer surface. The Ti-6Al-4V substrate, which has a base hardness of approximately 350 HV, experienced a drastic increase in hardness after being coated with the multi-layer system. The outermost layer containing WC-Co (with a 60:40 ratio in a NiCr matrix) is capable of achieving very high hardness values; in some studies, these have even been reported to exceed 900 HV (Du et al., 2022). This high hardness is a key factor in enhancing the material's wear resistance when subjected to extreme friction or erosion loads (Sharma et al., 2025).

This improvement in tribological performance is also influenced by the presence of carbide particles (WC and CrC) firmly embedded in the ductile NiCr metal matrix. This matrix not only holds the hard particles in place to prevent them from being easily dislodged (pull-out) but also provides the toughness required to absorb impact energy (Zhang et al., 2022). Data from the literature indicate that the material's coefficient of friction (CoF) decreases steadily compared to uncoated materials, suggesting the effectiveness of surface protection against mechanical degradation caused by cyclic loading (Du et al., 2022; Marimuthu et al., 2024).

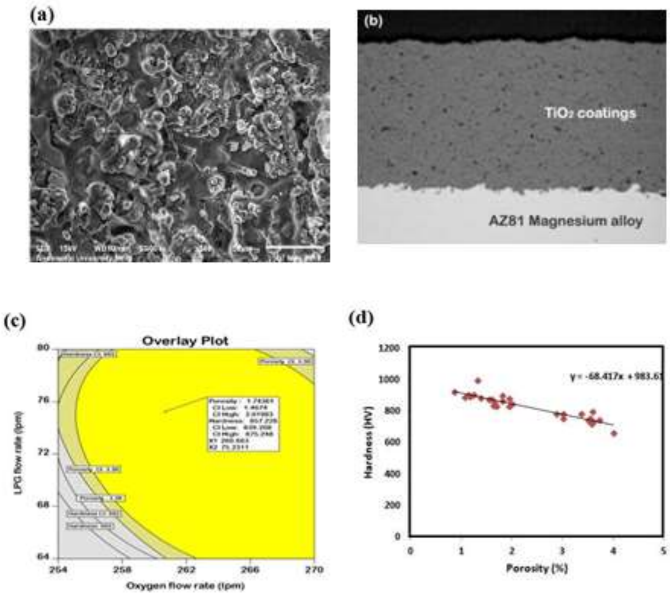

Figure 2. Microhardness profile graph from the substrate to the outer surface, showing the hardness gradient in the coating system.

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Fatigue Behavior and Residual Stress

In terms of corrosion resistance, the multi-layer system acts as a highly effective physical barrier. The CrC-NiCr intermediate layer plays a vital role because its high chromium content promotes the formation of a highly stable Cr_2O_3 passive oxide layer in aggressive environments, such as a 3.5% NaCl solution (Sharma et al., 2025). This passive layer actively inhibits the diffusion of chloride and oxygen ions, which typically trigger pitting corrosion in titanium alloys in marine or medical environments (Zhang et al., 2022).

Results from potentiodynamic polarization curve analysis (Tafel plots) in related studies show a shift in the corrosion potential (Icorr) toward more positive (noble) values and a significant decrease in corrosion current density (Icorr) (Sharma et al., 2025). This indicates that the metal dissolution rate on the coated surface is significantly slower compared to the uncoated specimen. The synergy between the density of the HVOF coating and the chemical properties of NiCr provides long-term protection for components exposed to corrosive environments (Anusha et al., 2025; Srinivasan et al., 2017).

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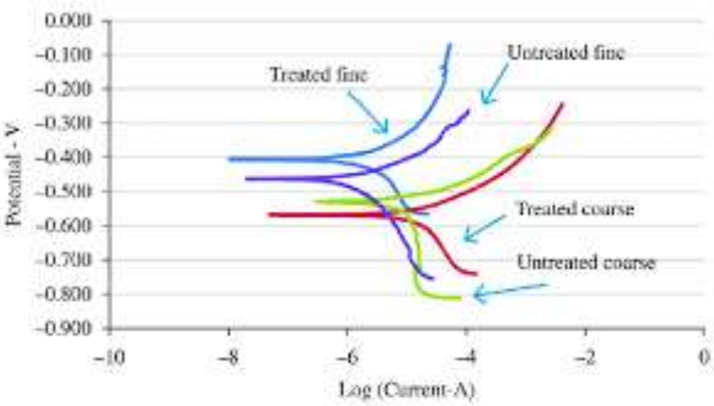

Figure 3. Potentiodynamic polarization curves (Tafel plots) showing a comparison of corrosion rates between uncoated specimens and those with multi-layer coatings

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Fatigue Performance and Crack Retention Mechanisms

The increase in fatigue life of Ti-6Al-4V coated with a multi-layer system is closely related to the induction of compressive residual stress generated by the HVOF process. When particles strike the surface at supersonic speeds, a micro-peening effect occurs that permanently compresses the substrate surface. This compressive residual stress acts in opposition to the operational tensile stress, thereby significantly inhibiting crack initiation on the material's surface (Anusha et al., 2025).

Additionally, the multi-layer structure design creates a discontinuous interface capable of deflecting crack propagation. If a crack begins to form in the outer WC-Co layer, which tends to be brittle, the crack will lose energy or change direction upon reaching the interface with the more ductile NiCr layer (Anusha et al., 2025; Zhang et al., 2022). This crack-retardation mechanism causes the number of material failure cycles to increase dramatically, making it an ideal solution for aerospace components operating under heavy vibration and cyclic loads.

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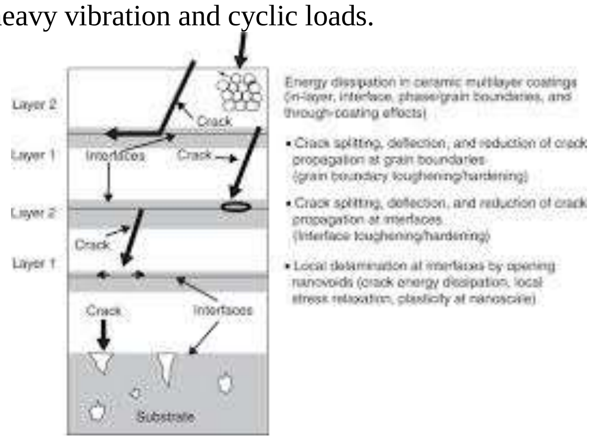

Figure 4. Schematic illustration of the crack deflection mechanism at the interface of a multi-layer coating system that enhances fatigue life

Additionally, the multi-layer structural design creates a discontinuous interface capable of deflecting the crack propagation path (crack deflection). If a crack begins to form in the outer WC-Co layer, which tends to be brittle, the crack will lose energy or change direction upon reaching the interface with the more ductile NiCr layer (Anusha et al., 2025; Zhang et al., 2022). This crack-retardation mechanism leads to a drastic increase in the number of failure cycles, making it an ideal solution for aerospace components operating under severe vibration and cyclic loads.

An in-depth discussion of these research results reveals a strong correlation between the multi-layer configuration and the increased service life of Ti-6Al-4V material. Cross-validation with various studies indicates that the key to this performance lies in the specific role allocation of each layer (NiCr, CrC-NiCr, and WC-Co). The NiCr layer, acting as a bond coat, not only enhances adhesion but also serves as a thermal shock absorber, preventing interface failure caused by differences in the coefficients of thermal expansion between the metal substrate and the carbide coating (Du et al., 2022; Srinivasan et al., 2017).

The relationship between layer configuration and fatigue life can be explained through the phenomenon of residual stress. The HVOF process intrinsically induces compressive residual stress on the substrate surface. This compressive stress effectively neutralizes the operational tensile stress that typically triggers the initiation of premature fatigue cracks (Anusha et al., 2025; Puchi-Cabrera et al., 2006). Consistent results across researchers confirm that, due to the multilayer structure, crack propagation energy is dissipated each time it passes through an interface between layers of differing ductility. This crack deflection mechanism significantly slows the crack growth rate toward the substrate, ultimately extending the overall service life of the material (Picas et al., 2017; Zhang et al., 2022).

In addition to mechanical factors, the service life stability of the material is also greatly influenced by surface chemical integrity. The relationship map indicates that the corrosion resistance provided by the CrC-NiCr layer prevents the formation of surface defects caused by corrosive ion attack (such as pitting). Surface defects resulting from corrosion act as stress risers, which are highly detrimental to fatigue resistance (Revie & Uhlig, 2025; Sharma et al., 2025). By inhibiting the corrosion process, the material surface remains smooth and free from chemical crack initiation; thus, the synergy between corrosion protection and the mechanical strengthening of WC-Co 60:40 results in a significantly more optimal service life compared to the use of a single-layer coating. This validation reinforces the argument that a multi-layer coating configuration is the most reliable surface design strategy for heavy-load applications in aggressive environments.

CONCLUSIONS

Based on a systematic literature review of recent studies, it can be concluded that the application of a multi-layer coating system using High Velocity Oxygen Fuel (HVOF) technology on Ti-6Al-4V alloys provides a significant and comprehensive improvement in surface performance. This technique produces highly dense coatings with porosity below 2%, while the NiCr bond coat plays a crucial role in ensuring strong adhesion and reducing thermal expansion mismatch between the substrate and the carbide layers. The incorporation of WC-Co (60:40) in the outermost layer generates a high hardness gradient, leading to enhanced wear resistance and improved surface stability compared to uncoated materials.

In addition to mechanical enhancement, the multi-layer coating system offers superior electrochemical protection through the formation of a stable chromium oxide passive layer, effectively reducing corrosion rates in aggressive environments. A key finding is the notable improvement in fatigue life, driven by the synergistic effects of compressive residual stresses induced during the HVOF process and crack deflection mechanisms at layer interfaces. This confirms that the coating system functions not only as a protective barrier but also as a structural reinforcement against cyclic loading failure.

Despite these promising outcomes, further studies are necessary to fully optimize and validate the coating performance under real service conditions. Future work should focus on combined corrosion-fatigue testing to better simulate operational environments, as well as optimization of layer thickness to achieve an ideal balance between hardness and ductility. Additionally, the integration of computational approaches, such as CFD-based simulations, is recommended to enhance coating deposition efficiency and interfacial quality, thereby reducing reliance on extensive experimental trials.

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