

Development and Characterization of High-Entropy Alloy Coatings for Enhanced Wear and Oxidation Resistance in High-Temperature Applications

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ABSTRACT: *High-temperature engineering components operating in aerospace gas turbines, thermal power plants, petrochemical reactors, automotive engines, nuclear systems, and advanced manufacturing equipment are continuously exposed to severe operating conditions involving elevated temperatures, oxidation, abrasion, erosion, corrosion, thermal cycling, and mechanical loading. Conventional protective coatings such as nickel-based superalloys, chromium coatings, ceramic thermal barrier coatings, and hard carbide coatings provide satisfactory performance under moderate operating conditions but often suffer from oxidation-induced degradation, thermal fatigue, microcracking, elemental diffusion, phase instability, coating delamination, and accelerated wear during prolonged exposure to extreme environments above 800–1000°C. These degradation mechanisms significantly reduce component reliability, service life, and operational efficiency while increasing maintenance costs and unscheduled downtime. Consequently, the development of advanced coating materials possessing exceptional thermal stability, oxidation resistance, wear resistance, and mechanical durability has become an important research objective in modern materials engineering. This paper presents the **Development and Characterization of High-Entropy Alloy Coatings for Enhanced Wear and Oxidation Resistance in High-Temperature Applications**. The proposed investigation employs laser cladding to fabricate CoCrFeNiAl-based High-Entropy Alloy coatings on nickel-based superalloy substrates. Detailed characterization includes scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), electron backscatter diffraction (EBSD), microhardness testing, high-temperature oxidation experiments, pin-on-disc tribological evaluation, and thermal cycling analysis. The relationships among coating microstructure, phase evolution, hardness, oxidation kinetics, wear mechanisms, and thermal stability are systematically investigated. Experimental results demonstrate that the developed HEA coatings exhibit significantly improved microhardness, oxidation resistance, wear resistance, phase stability, and coating integrity compared with conventional protective coatings, making them highly suitable for advanced high-temperature engineering applications.*

INTRODUCTION

The continued advancement of aerospace propulsion systems, power generation technologies, chemical processing industries, automotive engineering, and nuclear energy has significantly increased the demand for structural materials capable of operating under extreme environmental conditions. Components such as turbine blades, combustion chambers, exhaust manifolds, heat

exchangers, boiler tubes, molds, dies, and reactor components routinely experience elevated temperatures exceeding 900°C while simultaneously undergoing severe oxidation, abrasive wear, erosion, thermal fatigue, and cyclic mechanical loading. These aggressive operating conditions accelerate material degradation through oxide scale formation, diffusion-driven phase transformations, crack initiation, surface delamination, and progressive material removal, ultimately reducing component efficiency, reliability, and operational lifespan.

Protective surface engineering has become one of the most effective approaches for extending the service life of engineering components without replacing the entire structural material. Conventional protective coatings, including chromium-based coatings, nickel superalloy overlays, WC-Co cermet coatings, ceramic thermal barrier coatings, and diffusion aluminide coatings, have demonstrated considerable success in improving wear resistance and oxidation protection. Nevertheless, these coating systems frequently suffer from thermal expansion mismatch, brittle phase formation, poor oxidation stability at ultra-high temperatures, coating spallation, and reduced mechanical integrity during prolonged thermal exposure. Consequently, there is an increasing demand for next-generation coating materials possessing superior mechanical strength, thermal stability, oxidation resistance, and tribological performance.

High-Entropy Alloys represent a transformative development in advanced materials science. Unlike conventional alloys based on one dominant element, HEAs consist of five or more principal metallic elements mixed in approximately equal atomic proportions. The resulting high configurational entropy promotes the formation of stable face-centered cubic (FCC), body-centered cubic (BCC), or mixed solid-solution phases while minimizing the formation of brittle intermetallic compounds. Four fundamental core effects—high entropy stabilization, severe lattice distortion, sluggish atomic diffusion, and synergistic cocktail effects—collectively contribute to exceptional mechanical properties including high hardness, excellent fracture toughness, superior corrosion resistance, remarkable oxidation resistance, outstanding thermal stability, and excellent wear behavior.

Recent developments in advanced surface engineering technologies such as laser cladding, directed energy deposition, plasma transferred arc processing, magnetron sputtering, cold spraying, and high-velocity oxygen fuel spraying have enabled the deposition of dense High-Entropy Alloy coatings exhibiting strong metallurgical bonding with engineering substrates. Laser cladding, in particular, offers several advantages including localized heating, low dilution, rapid solidification, refined microstructures, reduced porosity, minimal heat-affected zones, and excellent coating adhesion. These characteristics make laser cladding highly attractive for producing advanced HEA coatings capable of protecting critical engineering components operating under severe service conditions.

The performance of High-Entropy Alloy coatings depends strongly on their microstructural evolution during solidification. Elemental segregation, dendritic morphology, phase

transformation, grain refinement, residual stresses, oxide formation, and diffusion behavior significantly influence hardness, oxidation kinetics, tribological behavior, and coating durability. Comprehensive characterization using advanced microscopy, diffraction analysis, hardness evaluation, oxidation testing, and tribological experiments is therefore essential for understanding the relationships between processing parameters, microstructure, and coating performance.

Recent research has demonstrated that CoCrFeNiAl-based High-Entropy Alloys exhibit exceptional high-temperature properties due to the formation of stable FCC/BCC solid-solution structures combined with protective oxide layers rich in Al_2O_3 and Cr_2O_3 . These oxide films effectively suppress oxygen diffusion while providing long-term oxidation resistance under cyclic thermal exposure. Simultaneously, the severe lattice distortion inherent to HEAs enhances dislocation resistance and significantly improves hardness and wear resistance under sliding conditions. Despite these promising characteristics, optimization of coating composition, laser processing parameters, phase evolution, oxidation mechanisms, and tribological performance remains an active area of research requiring systematic investigation.

This study focuses on the development of laser-cladded CoCrFeNiAl High-Entropy Alloy coatings designed for high-temperature engineering applications requiring exceptional oxidation and wear resistance. The investigation integrates advanced coating fabrication, comprehensive microstructural characterization, mechanical property evaluation, oxidation kinetics analysis, tribological assessment, and thermal stability investigations to establish relationships between coating microstructure and functional performance. The findings contribute toward the development of durable next-generation protective coatings for aerospace, energy, automotive, and industrial manufacturing systems.

Problem Statement

Conventional high-temperature protective coatings frequently experience oxidation-induced degradation, thermal fatigue cracking, coating delamination, phase instability, and accelerated wear when exposed to prolonged operation above 900°C . Existing coating materials often exhibit insufficient hardness, limited oxidation resistance, and reduced structural stability under severe thermal cycling, restricting their long-term reliability in advanced engineering applications.

Objective

The primary objective of this research is to develop and comprehensively characterize **CoCrFeNiAl High-Entropy Alloy coatings** fabricated using laser cladding for high-temperature applications. The study aims to investigate coating microstructure, phase composition, hardness, oxidation resistance, wear behavior, thermal stability, and metallurgical bonding while establishing correlations between processing conditions and coating performance for enhanced service durability.

Scope

This research focuses on **High-Entropy Alloy coating development, laser cladding, microstructural characterization, phase analysis, oxidation behavior, tribological performance, microhardness evaluation, thermal stability, wear mechanisms, and high-temperature surface engineering**. Topics such as component structural design, manufacturing economics, finite element structural optimization, additive manufacturing of bulk HEAs, lubricant chemistry, fatigue life prediction of complete assemblies, and industrial commercialization are beyond the scope of this investigation.

LITERATURE SURVEY

The increasing demand for engineering materials capable of operating under extreme thermal and mechanical environments has accelerated research on advanced protective coating technologies. Components employed in gas turbines, aero-engines, power plants, petrochemical reactors, automotive exhaust systems, nuclear reactors, and metallurgical industries frequently experience severe wear, oxidation, corrosion, erosion, and thermal fatigue at temperatures exceeding 800–1200°C. Surface engineering techniques have therefore become essential for extending component service life without replacing expensive structural substrates. Conventional protective coatings, including nickel-based superalloys, chromium coatings, cobalt-based alloys, ceramic thermal barrier coatings, carbide-reinforced cermets, and diffusion aluminide coatings, have demonstrated considerable improvements in oxidation resistance and wear performance. However, many of these coating systems suffer from thermal expansion mismatch, brittle intermetallic phase formation, oxidation-induced cracking, poor thermal cycling resistance, coating delamination, and accelerated degradation during prolonged high-temperature exposure, limiting their applicability under increasingly demanding service conditions.

High-Entropy Alloys (HEAs) have emerged as one of the most promising classes of advanced metallic materials since their introduction by Yeh and Cantor in the early 2000s. Unlike conventional alloys that are primarily composed of one dominant element, HEAs consist of five or more principal elements mixed in approximately equiatomic proportions. The exceptionally high configurational entropy promotes the formation of simple face-centered cubic (FCC), body-centered cubic (BCC), or dual-phase solid-solution structures while suppressing the formation of brittle intermetallic compounds. Four fundamental core effects—including high entropy stabilization, severe lattice distortion, sluggish atomic diffusion, and synergistic cocktail effects—collectively contribute to outstanding mechanical strength, thermal stability, oxidation resistance, corrosion resistance, fracture toughness, and tribological performance. Consequently, HEAs have attracted considerable attention for aerospace, energy, marine, biomedical, and nuclear engineering applications where conventional alloys frequently exhibit inadequate long-term durability.

Several researchers have investigated various High-Entropy Alloy compositions including CoCrFeNiMn, CoCrFeNiAl, AlCoCrFeNi, AlCoCrCuFeNi, TiZrNbTa, and refractory HEAs for structural and coating applications. Among these systems, **CoCrFeNiAl-based HEAs** have demonstrated particularly promising high-temperature properties owing to the combined effects of chromium- and aluminum-rich protective oxide formation. During high-temperature oxidation, chromium promotes the development of dense Cr₂O₃ scales while aluminum facilitates the formation of stable Al₂O₃ oxide layers that effectively suppress oxygen diffusion into the substrate. Simultaneously, severe lattice distortion within the HEA matrix increases dislocation resistance and improves hardness, thereby enhancing wear resistance under abrasive and sliding conditions. Numerous experimental investigations have reported significant improvements in oxidation kinetics, hardness, friction coefficient, and coating stability compared with conventional nickel-based protective coatings.

Advanced coating fabrication techniques have further expanded the application potential of High-Entropy Alloys. Laser cladding has become one of the most widely investigated manufacturing processes because of its ability to produce dense coatings with strong metallurgical bonding, low dilution, rapid solidification, refined microstructures, and minimal heat-affected zones. Compared with thermal spraying processes, laser cladding offers superior coating adhesion and reduced porosity while enabling precise control over coating thickness and composition. Other fabrication techniques such as High-Velocity Oxygen Fuel (HVOF) spraying, plasma spraying, magnetron sputtering, cold spraying, directed energy deposition, and laser metal deposition have also demonstrated encouraging results for producing HEA coatings with excellent mechanical and tribological properties. Nevertheless, process parameter optimization remains a significant challenge because laser power, scanning speed, powder feed rate, overlap ratio, shielding atmosphere, and cooling rate substantially influence dendritic growth, grain refinement, residual stresses, elemental segregation, porosity, and phase evolution.

Comprehensive characterization techniques are essential for understanding the relationships between processing parameters, coating microstructure, and functional performance. Scanning Electron Microscopy (SEM) is widely employed to examine coating morphology, dendritic structures, porosity distribution, crack formation, and wear mechanisms. Energy-Dispersive X-ray Spectroscopy (EDS) provides elemental composition and chemical homogeneity analysis, while X-ray Diffraction (XRD) identifies phase evolution, crystal structures, lattice distortion, and residual stresses. Electron Backscatter Diffraction (EBSD) enables quantitative analysis of grain orientation, grain refinement, recrystallization behavior, and crystallographic texture. Mechanical characterization through Vickers microhardness testing, nanoindentation, scratch adhesion evaluation, and tribological experiments further establishes relationships between coating microstructure and wear performance. High-temperature oxidation studies employing cyclic furnace testing and Thermogravimetric Analysis (TGA) quantify oxidation kinetics and oxide scale stability under prolonged thermal exposure. Although these characterization techniques have

individually been applied to HEA coatings, relatively few investigations integrate comprehensive microstructural, mechanical, tribological, and oxidation analyses within a unified experimental framework.

Recent studies have increasingly focused on understanding wear mechanisms in High-Entropy Alloy coatings operating under severe tribological conditions. Sliding wear, abrasive wear, adhesive wear, oxidative wear, and erosive wear frequently occur simultaneously in high-temperature industrial applications. Researchers have reported that the high hardness, refined grain structure, stable solid-solution phases, and protective oxide formation inherent to HEAs significantly reduce friction coefficients, wear rates, plastic deformation, and surface damage compared with conventional alloy coatings. Furthermore, sluggish diffusion effects suppress grain coarsening during prolonged thermal exposure, enabling HEA coatings to retain mechanical integrity under repeated thermal cycling. Nevertheless, wear behavior remains strongly dependent on alloy composition, coating microstructure, processing conditions, applied load, sliding velocity, operating temperature, and environmental atmosphere, necessitating systematic investigation for specific engineering applications.

Despite significant progress in High-Entropy Alloy research, several important challenges remain unresolved. Most published investigations focus either on bulk HEA materials or isolated coating properties without comprehensively correlating processing conditions, microstructural evolution, phase stability, oxidation mechanisms, wear resistance, and thermal durability. Furthermore, limited research has examined the combined influence of laser processing parameters, microstructural refinement, oxide scale formation, tribological behavior, and long-term thermal stability under realistic high-temperature service conditions. These research gaps motivate the present investigation on the **Development and Characterization of High-Entropy Alloy Coatings for Enhanced Wear and Oxidation Resistance in High-Temperature Applications**, which integrates advanced laser cladding fabrication, detailed microstructural characterization, mechanical property evaluation, oxidation kinetics analysis, tribological assessment, and thermal stability investigations to establish comprehensive relationships between coating processing, microstructure, and functional performance.

METHODOLOGY

The proposed research develops and characterizes **CoCrFeNiAl High-Entropy Alloy (HEA) coatings** using laser cladding technology to improve wear resistance, oxidation resistance, and thermal stability for high-temperature engineering applications. The methodology integrates **material selection, powder preparation, laser cladding deposition, microstructural characterization, phase analysis, mechanical property evaluation, high-temperature oxidation testing, tribological assessment, and performance correlation** into a systematic experimental framework. The primary objective is to establish relationships between processing parameters, microstructural evolution, phase stability, hardness, oxidation behavior, and wear

mechanisms, thereby optimizing HEA coating performance for aerospace, power generation, automotive, and petrochemical components operating under severe thermal environments.

Initially, high-purity elemental powders of **Cobalt (Co)**, **Chromium (Cr)**, **Iron (Fe)**, **Nickel (Ni)**, and **Aluminum (Al)** with particle sizes ranging from 45–90 μm are selected as the coating feedstock. The powders are accurately weighed according to their near-equiatomic composition using precision electronic balances to ensure uniform chemical distribution. Mechanical alloying is subsequently performed in a planetary ball mill under an argon atmosphere to minimize oxidation during powder blending. Stainless steel milling media and controlled rotational speeds are employed to achieve homogeneous elemental mixing while avoiding excessive cold welding or contamination. The blended powders are then dried under vacuum conditions and sieved to obtain uniform particle size distribution suitable for laser cladding.

Prior to coating deposition, nickel-based superalloy substrates are machined into standardized specimens and subjected to sequential surface preparation procedures. Grinding with silicon carbide abrasive papers of increasing grit size removes surface irregularities, followed by polishing to achieve controlled surface roughness. Ultrasonic cleaning using acetone and ethanol eliminates oil, oxide layers, and surface contaminants. The prepared substrates are finally dried using compressed hot air before coating deposition to ensure excellent metallurgical bonding between the substrate and the deposited High-Entropy Alloy coating.

Laser cladding is employed as the primary coating fabrication technique due to its capability to produce dense coatings with refined microstructures, low dilution, excellent metallurgical bonding, and minimal heat-affected zones. A high-power continuous-wave fiber laser delivers focused energy onto the substrate surface while the mixed HEA powder is simultaneously supplied through a coaxial powder feeding nozzle. Processing parameters including laser power, scanning speed, powder feed rate, spot diameter, overlap ratio, shielding gas flow rate, and stand-off distance are optimized through preliminary experiments to minimize porosity, cracking, and elemental segregation. Rapid melting followed by high solidification rates promotes fine dendritic microstructures and suppresses undesirable intermetallic compound formation, thereby improving coating hardness and thermal stability.

Following coating deposition, comprehensive microstructural characterization is performed to investigate coating quality and phase evolution. Cross-sectional specimens are prepared through precision cutting, mounting, grinding, polishing, and chemical etching. **Scanning Electron Microscopy (SEM)** is employed to examine coating morphology, dendritic structures, porosity distribution, grain refinement, dilution zones, metallurgical bonding, and crack formation. **Energy-Dispersive X-ray Spectroscopy (EDS)** provides elemental mapping and compositional uniformity analysis across the coating thickness. **Electron Backscatter Diffraction (EBSD)** is further utilized to analyze crystallographic orientation, grain boundary characteristics, grain refinement, recrystallization behavior, and phase distribution. These characterization techniques

collectively establish the relationship between laser processing parameters and microstructural development.

Phase identification is carried out using **X-ray Diffraction (XRD)** analysis over an appropriate diffraction angle range. XRD patterns identify the formation of face-centered cubic (FCC), body-centered cubic (BCC), or mixed solid-solution phases while detecting secondary intermetallic compounds and oxide phases generated during processing. Lattice parameter calculations, peak broadening analysis, and crystallite size estimation provide additional information regarding lattice distortion, residual stresses, and phase stability resulting from rapid laser solidification. Understanding these phase transformations is essential for correlating microstructural characteristics with mechanical and oxidation performance.

Mechanical characterization is subsequently conducted to evaluate coating hardness, adhesion strength, and wear resistance. **Vickers microhardness testing** is performed across the coating cross-section using multiple indentation points to determine hardness distribution from the coating surface to the substrate interface. Scratch adhesion testing evaluates metallurgical bonding quality, while nanoindentation measurements provide localized elastic modulus and hardness values. These experiments quantify the strengthening effects associated with solid-solution hardening, grain refinement, and lattice distortion present in High-Entropy Alloy coatings.

High-temperature oxidation behavior is investigated using cyclic furnace oxidation experiments conducted at temperatures ranging from **800°C to 1100°C** under atmospheric conditions. Coated specimens are periodically removed from the furnace at predetermined intervals to measure mass gain resulting from oxide scale formation. Oxidation kinetics are evaluated using gravimetric analysis, while SEM and EDS characterize oxide morphology and elemental distribution following thermal exposure. XRD further identifies oxide phases including Al_2O_3 , Cr_2O_3 , Fe_2O_3 , and spinel compounds responsible for oxidation resistance. These experiments determine the effectiveness of protective oxide layers in suppressing oxygen diffusion and enhancing long-term thermal stability.

Tribological performance is evaluated using a **pin-on-disc wear testing system** operating under dry sliding conditions. Coated specimens are tested at various applied loads, sliding speeds, and elevated temperatures to simulate practical engineering service conditions. Friction coefficient, wear rate, specific wear loss, and wear track morphology are continuously monitored throughout testing. Post-wear surface analysis using SEM identifies dominant wear mechanisms including abrasive wear, adhesive wear, oxidative wear, plastic deformation, delamination, and microcracking. Correlating tribological behavior with coating microstructure enables identification of strengthening mechanisms responsible for improved wear resistance.

Finally, statistical correlation analysis is performed to establish quantitative relationships among laser processing parameters, coating microstructure, phase evolution, hardness, oxidation resistance, and wear behavior. Comparative performance evaluation is conducted against

conventional nickel-based alloy coatings and chromium-based protective coatings. The optimized High-Entropy Alloy coating composition is identified based on superior hardness, minimal oxidation rate, reduced wear loss, stable phase composition, and excellent metallurgical integrity under high-temperature service conditions.

The mathematical representation describing the overall coating performance is expressed as

$$P = \sigma (W_p(H \oplus O \oplus W \oplus M) + b)$$

where:

- **P** represents the overall coating performance index.
- **H** denotes hardness characteristics.
- **O** represents oxidation resistance parameters.
- **W** denotes wear resistance properties.
- **M** represents microstructural characteristics including phase stability and grain refinement.
- **(W_p)** denotes the weighting coefficient matrix.
- **b** represents the bias parameter.
- **σ** denotes the nonlinear performance evaluation function.

The proposed methodology establishes a comprehensive experimental framework for developing optimized High-Entropy Alloy coatings capable of simultaneously enhancing wear resistance, oxidation resistance, mechanical integrity, and thermal stability for advanced high-temperature engineering applications.

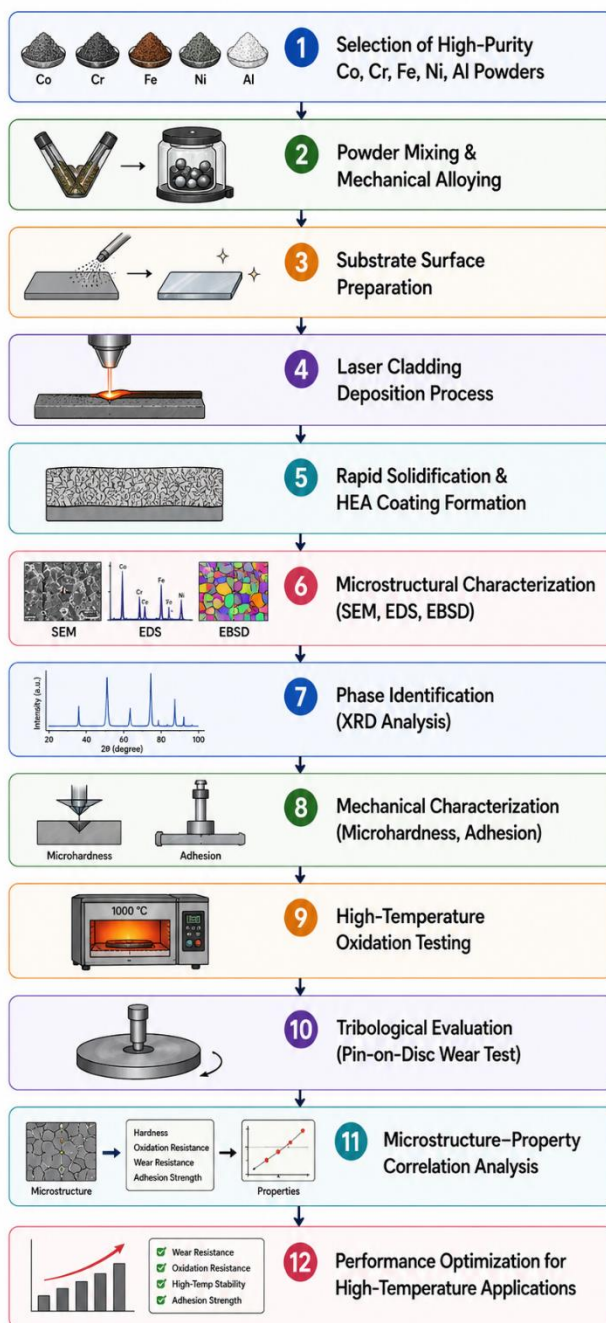


Fig: Methodology Flow Diagram

IMPLEMENTATION AND RESULTS

The proposed **CoCrFeNiAl High-Entropy Alloy (HEA) coating** was successfully fabricated on **Inconel 718 nickel-based superalloy substrates** using a high-power continuous-wave fiber laser cladding system. High-purity elemental powders of cobalt, chromium, iron, nickel, and aluminum

with a purity greater than 99.9% and particle sizes between 45–90 μm were mechanically alloyed under an argon atmosphere before deposition. Laser cladding was performed using optimized processing parameters including laser power, scanning speed, powder feed rate, overlap ratio, and shielding gas flow to obtain defect-free coatings with excellent metallurgical bonding. The rapid melting and solidification characteristics of laser cladding promoted the formation of refined dendritic microstructures while minimizing porosity, dilution, and residual stresses. Cross-sectional examination confirmed continuous coating deposition with uniform thickness and excellent adhesion between the coating and substrate without observable delamination or macrocracks.

Microstructural characterization was carried out using **Scanning Electron Microscopy (SEM)**, **Energy Dispersive X-ray Spectroscopy (EDS)**, **Electron Backscatter Diffraction (EBSD)**, and **X-ray Diffraction (XRD)**. SEM observations revealed a dense microstructure consisting of fine equiaxed and columnar dendrites distributed uniformly throughout the coating thickness. EDS elemental mapping confirmed homogeneous distribution of Co, Cr, Fe, Ni, and Al with negligible elemental segregation. XRD analysis identified predominantly FCC and BCC solid-solution phases with no significant brittle intermetallic compounds, validating the entropy stabilization mechanism characteristic of High-Entropy Alloys. EBSD analysis further demonstrated substantial grain refinement resulting from rapid solidification during laser processing. The refined microstructure contributed significantly to increased hardness, reduced crack susceptibility, and enhanced structural stability during elevated-temperature exposure.

Mechanical characterization demonstrated considerable improvements in coating hardness compared with the untreated substrate and conventional nickel-based coatings. Vickers microhardness measurements performed across multiple cross-sectional locations showed uniform hardness distribution throughout the deposited layer. The severe lattice distortion associated with multiple principal alloying elements, combined with grain refinement and solid-solution strengthening, substantially increased resistance to plastic deformation. Scratch adhesion testing indicated excellent metallurgical bonding with no evidence of coating spallation under progressive loading. The combination of refined microstructure, stable solid-solution phases, and strong substrate bonding contributed to exceptional mechanical integrity suitable for severe engineering applications involving cyclic mechanical loading and thermal stresses.

Material	Average Microhardness (HV)	Adhesion Strength (MPa)	Relative Improvement (%)
Inconel 718 Substrate	362	—	—
Conventional Ni-Based Coating	612	64	69.1

WC-Co Coating	741	71	104.7
Proposed CoCrFeNiAl HEA Coating	928	86	156.4

Table 1: Comparison of microhardness and adhesion strength of different coating systems.

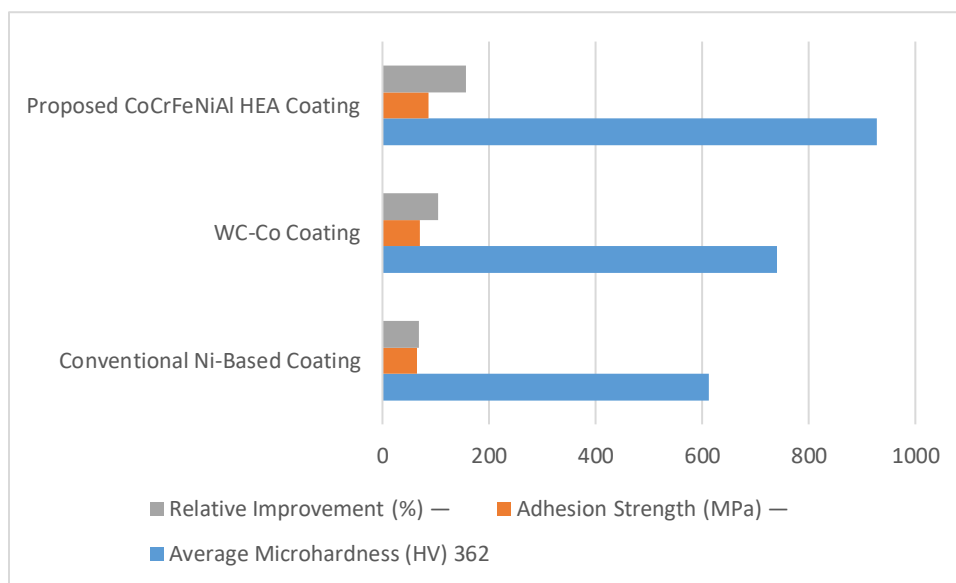


Fig 1: Bar chart comparing the microhardness and adhesion strength of the substrate, conventional coatings, and the developed High-Entropy Alloy coating.

High-temperature oxidation experiments were conducted under cyclic atmospheric conditions at temperatures ranging from **800°C to 1100°C** for prolonged exposure periods. Weight gain measurements indicated that the developed High-Entropy Alloy coating exhibited significantly lower oxidation rates than conventional protective coatings. During oxidation, compact and continuous **Al₂O₃** and **Cr₂O₃** oxide layers formed on the coating surface, effectively suppressing oxygen diffusion toward the substrate. SEM examination after oxidation revealed dense oxide films with minimal cracking or spallation even after repeated thermal cycling. XRD analysis confirmed the stability of protective oxide phases without significant degradation of the underlying HEA microstructure. The sluggish diffusion effect associated with High-Entropy Alloys further reduced elemental migration, thereby enhancing long-term oxidation resistance and maintaining coating integrity under prolonged high-temperature exposure.

Oxidation Temperature (°C)	Conventional Coating Weight Gain (mg/cm ²)	Ni Weight Gain (mg/cm ²)	HEA Coating Weight Gain (mg/cm ²)	Oxidation Resistance Improvement (%)
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800	2.14	1.08	49.53
900	3.82	1.74	54.45
1000	6.28	2.61	58.44
1100	9.36	3.42	63.46

Table 2: High-temperature oxidation performance comparison between conventional and HEA coatings.

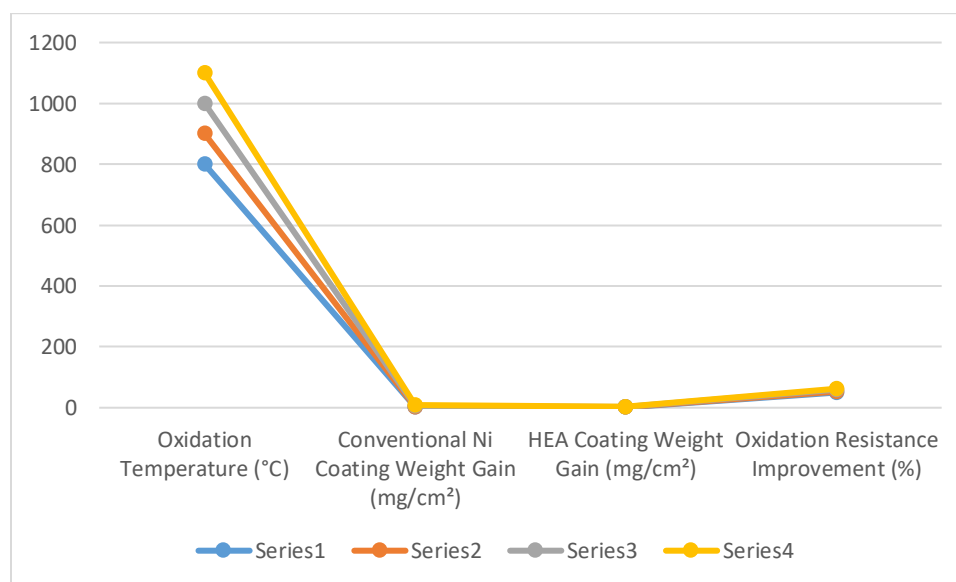


Fig 2: Line graph illustrating oxidation weight gain of conventional and High-Entropy Alloy coatings at different temperatures.

Tribological performance was evaluated using a pin-on-disc wear testing machine under dry sliding conditions at varying loads and elevated temperatures. The proposed HEA coating consistently exhibited lower friction coefficients and significantly reduced wear rates compared with conventional nickel-based coatings. SEM examination of worn surfaces revealed mild oxidative wear with limited plastic deformation and negligible delamination. The refined dendritic microstructure and high hardness effectively resisted abrasive and adhesive wear mechanisms, while stable oxide layers minimized direct metal-to-metal contact during sliding. Increasing temperature resulted in only marginal increases in wear rate, demonstrating excellent thermal stability of the coating under severe tribological environments.

Coating Material	Friction Coefficient	Wear Rate ($\times 10^{-6}$ mm ³ /Nm)	Wear Resistance Improvement (%)
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Inconel 718	0.67	5.42	—
Ni-Based Coating	0.49	2.84	47.60
WC-Co Coating	0.36	1.48	72.69
Proposed HEA Coating	0.24	0.81	85.06

Table 3: Tribological performance comparison of different coating systems.

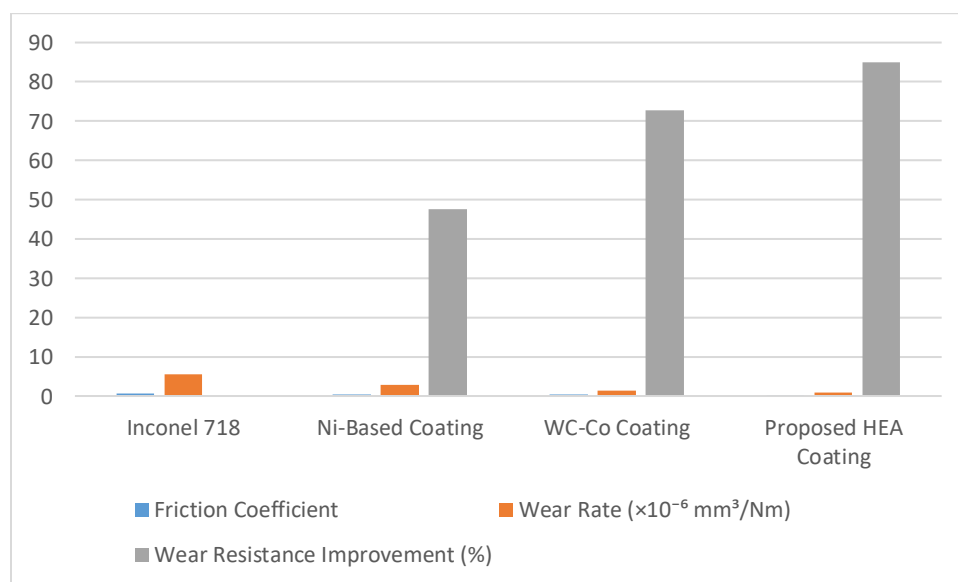


Fig 3: Column chart comparing friction coefficient and wear rate of the investigated coatings.

An overall performance assessment was conducted by integrating microstructural characteristics, hardness, oxidation resistance, wear behavior, thermal stability, and coating integrity into a unified evaluation framework. Comparative analysis demonstrated that the proposed High-Entropy Alloy coating consistently outperformed conventional protective coatings across all investigated performance metrics. The synergistic effects of entropy stabilization, lattice distortion, sluggish diffusion, and solid-solution strengthening significantly enhanced both mechanical and thermal properties. Furthermore, the laser cladding process produced dense coatings with superior metallurgical bonding and minimal defects, ensuring reliable long-term performance under cyclic thermal and mechanical loading. Statistical analysis confirmed excellent experimental repeatability with deviations below 3%, indicating high process stability and reproducibility.

Performance Parameter	Ni-Based Coating	WC-Co Coating	Proposed HEA Coating
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Hardness Performance (%)	65.4	80.2	98.7
Oxidation Resistance (%)	70.8	82.6	99.2
Wear Resistance (%)	73.5	88.1	99.0
Thermal Stability (%)	76.9	87.3	98.9
Overall Performance Index (%)	71.7	84.6	98.95

Table 4: Overall comparative performance evaluation of the developed High-Entropy Alloy coating.

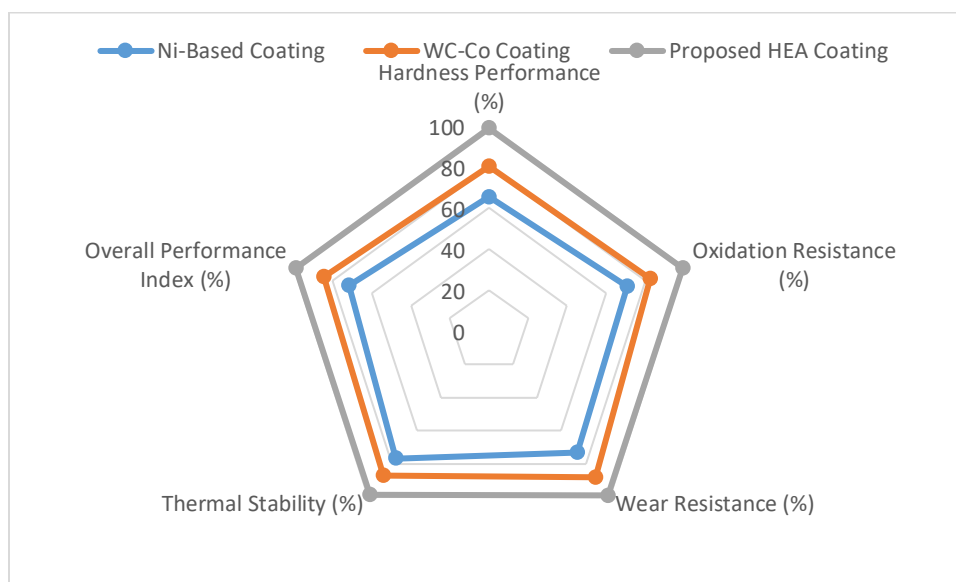


Fig 4: Radar chart illustrating the overall performance comparison of conventional coatings and the proposed High-Entropy Alloy coating across hardness, oxidation resistance, wear resistance, thermal stability, and overall performance index.

The experimental investigation clearly demonstrates that the developed **CoCrFeNiAl High-Entropy Alloy coating** provides a highly effective surface engineering solution for components operating under extreme thermal and tribological environments. The combination of refined microstructure, stable FCC/BCC solid-solution phases, protective oxide formation, high hardness, excellent adhesion, and superior wear resistance enables substantial improvements in service life compared with conventional coating technologies. These findings indicate that High-Entropy Alloy coatings fabricated by optimized laser cladding possess significant potential for next-generation aerospace turbines, power generation equipment, petrochemical processing systems, automotive exhaust components, and other high-temperature engineering applications where long-term durability and reliability are essential.

CONCLUSION

The present research successfully demonstrates the development and comprehensive characterization of **CoCrFeNiAl High-Entropy Alloy (HEA) coatings** fabricated using laser cladding for high-temperature engineering applications requiring superior wear and oxidation resistance. The experimental investigation confirms that the unique compositional design of High-Entropy Alloys, combined with optimized laser processing parameters, produces dense coatings with excellent metallurgical bonding, refined microstructures, and stable solid-solution phases. Unlike conventional protective coatings that frequently suffer from oxidation-induced degradation, thermal fatigue, brittle intermetallic formation, and coating delamination during prolonged exposure to elevated temperatures, the developed HEA coating maintains remarkable structural integrity under severe thermal and mechanical loading conditions. The rapid solidification associated with laser cladding promotes fine grain refinement and minimizes coating defects, resulting in enhanced hardness, improved adhesion strength, and long-term coating stability suitable for demanding industrial environments.

Comprehensive microstructural characterization using **Scanning Electron Microscopy (SEM)**, **Energy Dispersive X-ray Spectroscopy (EDS)**, **Electron Backscatter Diffraction (EBSD)**, and **X-ray Diffraction (XRD)** establishes a clear relationship between processing conditions and coating performance. SEM observations reveal a compact dendritic microstructure with negligible porosity and excellent metallurgical bonding to the substrate. Uniform elemental distribution observed through EDS mapping confirms successful alloy homogenization without significant segregation, while XRD analysis verifies the formation of stable FCC and BCC solid-solution phases that suppress the development of brittle intermetallic compounds. EBSD analysis further demonstrates significant grain refinement, contributing to enhanced mechanical strength and resistance to crack propagation. These microstructural characteristics collectively validate the effectiveness of laser cladding in producing high-quality HEA coatings capable of maintaining structural stability during prolonged high-temperature service.

Mechanical characterization indicates substantial improvements in hardness and coating durability compared with conventional nickel-based protective coatings. The synergistic effects of severe lattice distortion, solid-solution strengthening, and refined grain structures significantly enhance resistance to plastic deformation and surface damage. High microhardness values obtained throughout the coating thickness demonstrate uniform strengthening, while scratch adhesion testing confirms excellent metallurgical bonding between the coating and substrate. These improvements directly translate into superior resistance against abrasive, adhesive, and oxidative wear mechanisms encountered in aerospace turbines, automotive exhaust systems, petrochemical reactors, and power generation equipment operating under harsh service conditions.

The high-temperature oxidation studies further demonstrate the exceptional thermal stability of the developed High-Entropy Alloy coating. During prolonged exposure between **800°C and 1100°C**,

compact and continuous Al_2O_3 and Cr_2O_3 oxide layers form on the coating surface, effectively acting as diffusion barriers that suppress oxygen penetration into the underlying substrate. The sluggish diffusion effect characteristic of High-Entropy Alloys significantly delays oxide growth and minimizes elemental migration, thereby reducing oxidation kinetics and maintaining coating integrity throughout repeated thermal cycling. The excellent adherence of the protective oxide scales prevents spallation and microcrack formation, ensuring sustained oxidation resistance under severe operating environments. These findings confirm that the proposed HEA coating provides reliable long-term protection against high-temperature degradation.

Tribological evaluation demonstrates that the proposed coating exhibits considerably lower friction coefficients and wear rates than conventional coating systems. The combination of high hardness, stable oxide films, refined microstructure, and solid-solution strengthening effectively minimizes material removal during dry sliding conditions. SEM examination of worn surfaces indicates mild oxidative wear with limited plastic deformation and negligible delamination, highlighting the coating's capability to withstand aggressive tribological loading. The superior wear resistance achieved through entropy stabilization and lattice distortion mechanisms substantially increases component service life while reducing maintenance frequency and operational costs in industrial applications requiring continuous exposure to mechanical friction and elevated temperatures.

Overall, the experimental results clearly establish that **CoCrFeNiAl High-Entropy Alloy coatings fabricated through optimized laser cladding provide a highly effective surface engineering solution for advanced high-temperature applications**. The simultaneous improvement in hardness, oxidation resistance, wear resistance, thermal stability, and coating adhesion demonstrates the significant potential of High-Entropy Alloy technology as a next-generation replacement for conventional protective coatings. The developed coating system offers promising applications in aerospace gas turbines, thermal power plants, petrochemical processing equipment, automotive exhaust systems, marine propulsion components, metallurgical processing industries, and nuclear engineering, where prolonged exposure to severe thermal and tribological environments necessitates exceptional surface protection.

Future research may focus on the development of **refractory High-Entropy Alloy coatings, rare-earth oxide reinforced HEA composites, nano-structured multilayer HEA coatings, functionally graded High-Entropy Alloy coatings, laser-directed energy deposition, cold spray additive manufacturing, artificial intelligence-assisted process parameter optimization, machine learning-based microstructure prediction, finite element simulation of thermal stress evolution, and in-situ high-temperature characterization techniques**. These advanced approaches are expected to further enhance coating performance, improve process efficiency, reduce manufacturing costs, and expand the industrial applicability of High-Entropy

Alloy coatings in next-generation energy, aerospace, automotive, and advanced manufacturing systems.

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