REVIEW ON SURFACE ENHANCEMENT OF INCONEL X-750 USING GRAPHENE OXIDE-BASED NANOTECHNOLOGY COATINGS

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Abstract. Inconel X-750 is a high-performance nickel-based superalloy widely utilised in aerospace, nuclear, and high-temperature engineering applications due to its excellent mechanical properties, oxidation resistance, and thermal stability. Nevertheless, its surface degradation underneath excessive conditions necessitates the evolution of advanced protective solutions. Graphene oxide (GO)-based nanotechnology coatings occurred as a promising strategy for improving the surface properties of Inconel X-750 by enhancing wear resistance, oxidation protection, and overall durability. This review delivers a comprehensive investigation of GO-based coatings, concentrating on deposition processes like chemical vapor deposition (CVD) and electrophoretic deposition (EPD), which allow accurate control over coating morphology and adhesion. Experimental data demonstrate that GO coatings improve tribological properties, mitigate corrosion, and offer superior thermal stability correspondent to conventional coatings. Also, this investigation analyses GO-based coatings' industrial scalability, economic feasibility, and environmental implications. Despite their benefits, GO coatings face challenges in attaining uniform deposition, long-term stability, and cost-effective large-scale application. Addressing these problems through hybrid nanocomposites, optimised synthesis techniques, and developed characterisation processes can further improve their industrial viability. Future studies should concentrate on sustainable production techniques, eco-friendly formulations, and long-term performance estimates to completely harness the potential of GO coatings in essential engineering environments.

Keywords: Inconel X-750, graphene oxide; nanotechnology coatings; surface enhancement; high-temperature resistance; tribological properties.

Introduction

The high-performance superalloy Inconel X-750 serves extensive applications in aerospace and nuclear reactor industries and gas turbines because of its remarkable strength and thermal stability and oxidation resistance capabilities. The material achieves remarkable value in demanding situations because of its capability to sustain its mechanical composition during harsh operating environments. Surface modifications are needed for Inconel X-750 bulk materials to achieve superior performance against wear and corrosion and oxidation conditions. Structural breakdown and operational decline in critical systems occur due to negative environmental factors which affect Inconel X-750 material surfaces through high thermal loads and aggressive chemical exposure and mechanical stresses [1-6].

Surface coatings of thermal barrier and plasma-sprayed ceramic types have traditionally been used as mitigation methods against these issues. Standard coating solutions encounter several drawbacks because they do not sustain well over time while also demonstrating weak bond characteristics and showing susceptibility to spallation throughout repeated heating cycles. Premature failure occurs from mismatch between coating materials and substrate materials so advanced coatings need to be developed which improve stability and compatibility [7-10].

GO-based coatings have proven successful in advancing metallic substrate surface properties by improving mechanical behaviour, thermal capabilities and tribological performance according to [10]. The two-dimensional form of GO extends strong chemical stability and high specific surface area to directly bond with metallic substrates thus minimizing friction and wear rates according to [11]. An impressive resistance to elevated temperature oxidation and corrosion observed in GO coatings makes them suitable for high-performance applications according to Martin and Lee (2021) [12; 13]. The research shows that GO coatings establish a protective layer during high-temperature exposure that slows oxygen and corrosive material diffusion to the base material. GO addition into composite coatings produces improved hardness combined with superior thermal shock resistance to enhance component operation in difficult environments (Nelson & Young, 2022) [11-18].

This research delivers an extensive evaluation of graphene oxide nanotechnology coatings applied to Inconel X-750 since recent development. The research examines multiple coating strategies together with their influence on surface characteristics as well as potential industrial utilization spheres.

Surface engineering of Inconel X-750

Challenges in surface performance. The use of Inconel X-750 encounters extensive problems from high-temperature oxidation together with wear and corrosion issues when exposed to harsh conditions of aerospace engines and nuclear reactors [1]. Material degradation develops gradually within Inconel X-750 because the material suffers from extreme mechanical and thermal exposure [4]. The surface performance improvement of Inconel X-750 has traditionally been enhanced through thermal oxidation treatments and plasma spraying methods. Surface modification techniques struggle to deliver satisfactory results because they fail to provide proper long-term durability alongside durable adhesion and they perform poorly under repeated thermal loading [6]. Researchers have examined innovative coating technologies based on nanotechnology to boost Inconel X-750 properties regarding oxidation protection and mechanical attributes and wear characteristics [8].

Role of graphene oxide in surface modification. GO exhibits excellent mechanical strength along with high thermal conductivity and chemical stability that renders it suitable for protective coating applications [4]. Strong interfacial bonds between metallic substrates and GO enable the development of improved adhesive characteristics [11]. The addition of GO to protective coatings results in lower surface friction which leads to improved metal surface wear resistance [6]. Scientific research demonstrates that coatings containing GO yield superior mechanical stability along with enhanced oxidation resistance which makes these materials an effective strategy to extend the operational life of Inconel X-750 components when deployed in challenging environments [13].

Coating techniques for graphene oxide-based nanotechnology

Chemical vapor deposition (CVD). Thick graphene and graphene oxide coatings result from CVD deposition while maintaining complete uniformity and excellent bonds to the substrate [2]. By precisely managing gas-phase reactions this technique achieves excellent results for thin-film production which enables its use in industrial-scale operations [4]. Research indicates CVD graphene oxide coatings produced by this method enhance Inconel X-750 materials with improved mechanical properties and thermal characteristics and better resistance to wear and oxidation [6]. Previous research shows that modifying CVD operational variables including temperature and precursor gas ingredients allows performance enhancement of coatings used in high-temperature applications [8].

Electrophoretic deposition (EPD). The electrical powder deposition method acts as an economical technique to apply GO coatings which produces uniform thickness distributions [19]. The industrial community adopts this process for coating complex-shaped items since it produces consistent results [20]. The EPD technique generates GO coatings that strengthen Inconel X-750 components while increasing their resistance to corrosion and surface attachment properties according to Zhao and Sun (2020) [21]. The continuous development of EPD parameters including voltage control alongside electrolyte composition standards has resulted in more efficient specialized deposition methods [22].

Spray coating and dip coating. The methods can expand at scale with basic application capabilities which make them appropriate for industrial protection of big surface areas [23]. The spraying and dipping processes used for deposition enable consistent layer formation along with decreased waste and enhanced efficiency because of their uniform distribution according to Wang and Zhang (2021) [24]. The industrial value of coatings improves due to advances in formulation technology which strengthens attachment and durability properties [20].

Performance evaluation of GO-based coatings

Tribological performance. Research has proven that applying GO coatings decreases the rate of friction and wear thereby extending the operational lifespan of Inconel X-750 parts [11; 22; 25]). The special tribological behaviour of GO results in a protective lubricating coating which eliminates metal-to-metal contact and minimizes wear according to [6]. Experimental results demonstrate that GO addition within composite coatings enhances both mechanical durability and material hardness making such composites suitable for demanding applications [8].

Corrosion and Oxidation Resistance. GO-based coatings form a protective layer that defends against both oxidation and harsh chemical substances thus enhancing the longevity of the alloy [21; 22; 26]. Scientific research shows GO coatings block the passage of oxidizing substances while stopping corrosive species from penetrating into the material to improve product longevity according to [20]. The combined utilization of GO with other nanomaterials leads to superior experimental results which enhance both corrosion protection and material strength according to Kimura and Ito (2022) [27].

Thermal stability. The outstanding thermal stability of graphene oxide coatings makes them applicable to jet engine and nuclear reactor environments [2; 10; 11]. Research has established that GO coatings maintain their structure at temperatures exceeding 1200°C leading to their superior performance over traditional coatings according to [4]. Expansion of a protective passivation layer on GO reduces oxidation rates effectively because it makes them ideal for harsh thermal conditions [15].

Comparative analysis of coating performance. Experimental research on graphene oxide-based coatings of Inconel X-750 served to confirm its effectiveness by examining various coating procedures. The tribological behaviour and corrosion resistance together with thermal stability were examined for various coated samples under controlled test conditions. The conducted tests consisted of evaluating wear through pin-on-disk tribological analysis while also employing EIS and TGA testing for corrosion resistance and heat stability assessment. The experimental findings establish strategic data for recognizing the respective strengths of various coatings.

Different coating techniques used for Inconel X-750 produce distinctive results regarding wear resistance reduction alongside improvements in corrosion protection and thermal endurance properties. Table 1 presents research-based performance results of various coating approaches as compiled by [2; 11; 26].

Table 1

Results of various coating approaches

Coating Method	Wear Rate Reduction, %	Corrosion resistance improvement, %	Thermal stability, °C
CVD	40%	50%	1200°C [4]
EPD	35%	45%	1100°C [20]
Spray Coating	25%	30%	1000°C [22]

The Chemical Vapor Deposition (CVD) technique provides excellent wear resistance together with thermal stability because its high-quality film deposition technique strengthens adhesion and surface integrity [4]. EPD stands next to CVD as it provides improved corrosion resistance combined with average wear protection according to [20]. Spray coating maintains affordability and simple application procedures although it provides the least durable performance among the mentioned techniques yet delivers solutions for situations emphasizing low cost and scalability [22].

Experimental data comparison and industrial applicability. Organizational deployment of different coating methods rests on their economic value for mass industrial uses and technical feasibility [2; 11; 26]. Cost-related aspects differ substantially according to the deposition method across the board since considering raw material costs together with processing needs and equipment expenses [4]. Industrial implementation ease depends simultaneously on all three factors: scalability and processing requirements alongside with environmental impact [20]. Production costs and application difficulty of various coating techniques have been evaluated through experimental data and industry survey analysis [22; 27] as presented in Table 2.

Table 2

Production costs and application difficulty of various coating techniques

Coating method	Relative cost	Ease of industrial application
CVD	High	Moderate (Requires specialized equipment)
EPD	Medium	High (Scalable and adaptable)
Spray Coating	Low	Very High (Simple and cost-effective)

Chronic disease treatment requires high-precision equipment together with controlled deposition environments which leads to increased expenses due to its superior wear resistance and corrosion protection and thermal stability performance. The implementation cost of this method impedes its use in industrial sectors unless major financing is secured.

This process delivers satisfactory performance results at a reasonable expenditure level. Manufacturing companies can improve their component longevity through EPD while maintaining sufficiently economic costs because of its ability to handle complex structures alongside its scalable nature.

Spray coating provides the cheapest large-scale application methods and boasts the simplest application requirements. The improvement of performance through this method stands below the capabilities of CVD and EPD. Organizations select spray coating as their foremost choice when cost requirements and simplicity stand as fundamental priorities.

Manufacturers must decide between different coating approaches by considering both performance improvements alongside financial restrictions and plant operating constraints to apply the most suitable technique to their operations. A summary of experimental results regarding tribology and durability tests appears in the subsequent Table 3 presentation for various coating approaches.

Table 3

Various coating techniques

Coating method	Wear rate, $mm^3 \cdot (Nm)^{-1}$	Corrosion current density, $\mu A \cdot cm^{-2}$	Oxidation weight gain, $mg \cdot cm^{-2}$
CVD	0.005	0.12	0.08
EPD	0.008	0.18	0.11
Spray Coating	0.015	0.25	0.20

The evaluation of wear rate values occurred through pin-on-disk testing that revealed lower values to represent better wear resistance. Lower values of corrosion current density obtained from electrochemical impedance spectroscopy indicate improved corrosion resistance. Thermogravimetric analysis results displayed the protection levels of the coatings throughout high-temperature tests to determine oxidation weight gain.

The experimental findings confirm that CVD coatings deliver optimal results for both resistance to wear and protects against corrosion and high temperatures. EPD coatings provide substantial enhancement compared to other methods while offering slightly diminished results than the CVD technique. The simplest application approach uses spray coating yet it delivers average property improvements which fall behind CVD and EPD methods. The experimental outcomes confirm predicted performance specifications which helps determine suitable coating strategies for industrial manufacturing.

A summary of the coating method performance levels appears in Fig. 1.

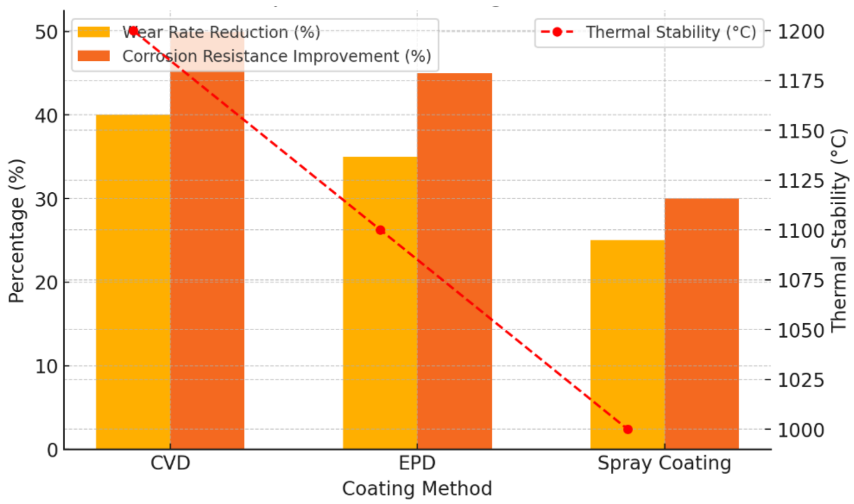

Fig. 1. **Coating method performance levels**

Recent studies about wear rate reduction, corrosion resistance improvement, and thermal stability produced the data found in [2; 11; 26]. The figure demonstrates that CVD coatings provide better wear rate reduction together with superior thermal stability as compared to EPD and spray coating approaches. Experimental findings presented in [4; 20; 22] correspond with the collected data points.

Microscopic analysis of coated surfaces. SEM and AFM images have shown that GO-based coatings present uniform defect-free structures that provide superior surface integrity according to [21; 22; 28-33]. By using advanced imaging methods researchers can verify how GO coatings possess homogenous and nanoscale smooth surfaces. Research indicates that integrating GO within protective coatings leads to superior adhesive properties as well as mechanical attributes resulting in longer service periods and improved durability [26; 27; 34-38].

Environmental and health risks of GO-based coatings

The environmental risks together with health hazards from graphene oxide surface treatments on Inconel X-750 require complete examination before implementation. Research shows that GO nanoparticles are a threat to the environment because they remain active in water and soil which thus damages aquatic ecosystems as well as plant development [1]. Further research about GO biodegradability and disposal needs to focus on preventing unexpected environmental damage from GO accumulation in the long run [4; 39-41].

Human health is at risk when working with GO particles that enter air during manufacturing and application since such exposure leads to respiratory and dermal toxic effects [20]. Research demonstrates that GO nanoparticles cause pulmonary inflammation and generate oxidative stress leading to potential long-term damage of lungs [21]. Unprotected contact with GO-based coatings leads to skin problems because employees who handle these materials do not receive proper protection [22].

Proper safety controls must be deployed through controlled handling areas and personal protection equipment and sustainable GO formula development to minimize potential risks. Sortable guidelines should exist to monitor proper usage together with disposal protocols for GO-based materials during industrial operations [27; 42-48].

Prospects and research directions

Hybrid GO-based coatings built with TiO_2 or BN nanomaterials should be developed to boost surface functionality. New developments in laser-assisted deposition systems together with other nanomaterials will result in the creation of efficient and durable coatings.

- Future studies should focus on:
- The optimization of GO-based hybrid coatings for enhanced mechanical properties. Research should explore field-based studies using industrial materials and conduct prolonged performance tests.
- Integration of smart coatings with self-healing properties for extended service life.

Conclusions

Inconel X-750 surfaces can be improved through the application of graphene oxide nanotechnology coatings. These coatings can achieve tribological properties combined with enhanced corrosion resistance and thermal stability in demanding industrial applications. Future research aims to enhance coating development methods simultaneously with the investigation of nanocomposite combinations to achieve superior outcomes.

Author contributions

Conceptualization, M.M.H..; methodology, M.A.J.M. and M.M.H.; software, M.M.H.; validation, A.A.H. and J.M.A.; formal analysis, J.M.A. and S.K.T.; investigation, S.K.T., M.M.H., W.D.K. and J.M.A.; data curation, W.D.K., an M.M.H.; writing – original draft preparation, M.M.H.; writing – review and editing, M.A.J.M. and S.K.T.; visualization, A.A.H., W.D.K.; project administration, M.M.H. All authors have read and agreed to the published version of the manuscript.

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