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Experimental Study of Tungsten Carbide Coating on Nickel Alloy

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ABSTRACT

Nickel-based superalloys are extensively utilized in turbine blades due to their outstanding high-temperature strength, oxidation resistance, and overall durability. Despite these advantages, they encounter significant challenges in extreme operating conditions. Limitations such as high production and processing costs, susceptibility to creep and fatigue under prolonged thermal exposure, and temperature constraints pose challenges to their performance. Additionally, while inherently resistant to oxidation and corrosion, these alloys are not entirely immune to such issues. Their relatively high density also adds to the weight of turbine components, impacting efficiency and functionality. These factors underline the need for advanced material solutions to improve turbine blade performance.

Tungsten carbide (WC) coatings offer a promising approach to address these challenges. Renowned for their exceptional hardness and resistance to wear, WC coatings can be applied to nickel alloy substrates to enhance their surface characteristics. Advanced deposition techniques, such as High-Velocity Oxygen Fuel (HVOF) spraying, enable the creation of robust tungsten carbide coatings that significantly improve surface hardness, thereby minimizing wear and erosion. This is especially beneficial in environments where mechanical wear poses a major concern. Moreover, these coatings provide a protective barrier against oxidation and corrosion, enhancing the high-temperature performance of turbine blades.

By mitigating the thermal and mechanical limitations of nickel-based superalloys, tungsten carbide coatings extend the operational lifespan of turbine blades while maintaining their structural integrity. The application of these coatings enables turbine blades to perform effectively under more extreme conditions.

INTRODUCTION

1.1 TURBINE BLADES

Turbine blades play an essential role in the functioning of turbine engines, which are integral to industries such as power generation and aerospace. These blades extract energy from the high- temperature and high-pressure gases generated during combustion. The overall efficiency and lifespan of turbine engines are heavily influenced by the performance and durability of the turbine blades.

In the early stages of turbine technology development, materials with basic high-temperature capabilities were used. Initially, steel and stainless steel were common materials due to their widespread availability and ease of manufacturing. However, these metals had limitations in terms of high-temperature strength and resistance to oxidation, which restricted their effectiveness and longevity in turbine blades.

To overcome these challenges, the development of superalloys marked a significant advancement. These alloys are specifically engineered to endure extreme temperatures and mechanical stresses. Nickel-based superalloys, in particular, became the material of choice for turbine blades due to their exceptional high-temperature strength, resistance to thermal creep, and corrosion resistance. Popular nickel-based superalloys include Inconel, Rene, and Hastelloy.

These superalloys are capable of maintaining their strength and stability even at temperatures above 1000°C. They often include elements like chromium, cobalt, aluminum, and titanium, which enhance their high-temperature properties. The incorporation of aluminum and titanium creates a gamma-prime (γ') phase, which strengthens the material through precipitation hardening.

In addition to nickel-based superalloys, cobalt-based alloys are also used in turbine blades. Alloys such as those in the Haynes and Stellite families offer excellent resistance to hot corrosion and thermal fatigue. While they may not match the high-temperature strength of nickel-based superalloys, their ability to endure cyclic thermal stresses makes them valuable in specific turbine applications.

1.2 NICKEL ALLOY

Nickel alloys and nickel-based superalloys have played a pivotal role in materials science, particularly in turbine applications, due to their exceptional performance at high temperatures, mechanical strength, and resistance to environmental degradation. This essay delves into the properties, development, and uses of nickel alloys and superalloys in turbines, along with the challenges involved in their application.

Nickel alloys are recognized for their outstanding resistance to oxidation, corrosion, and thermal fatigue. These characteristics are attributed to nickel's natural ability to form a protective oxide layer that shields the material beneath. Furthermore, nickel's face-centered cubic (FCC) crystal structure allows it to accommodate a variety of alloying elements, which enhance the material's strength and stability at high temperatures.

TUNGSTEN CARBIDE

Tungsten Carbide: Properties, Coating Applications, and Advantages

Introduction

Tungsten carbide (WC) is a compound composed of tungsten and carbon atoms in equal parts, renowned for its exceptional hardness, wear resistance, and high-temperature stability. These properties make tungsten carbide an ideal material for use as a coating to enhance the performance and longevity of tools, machinery, and components in a variety of industries. This essay explores the properties of tungsten carbide, its application as a coating, and the numerous advantages it offers.

Properties of Tungsten Carbide Hardness and Wear Resistance
Tungsten carbide is one of the hardest materials known, with a hardness rating of approximately 9 on the Mohs scale, just below diamond. This extreme hardness translates into exceptional wear resistance, which is critical for applications involving abrasive environments. The wear resistance of tungsten carbide significantly exceeds that of most other materials, making it ideal for extending the lifespan of components subjected to heavy wear.

High Melting Point
Tungsten carbide has a very high melting point of about 2,870°C (5,198°F). This high melting point allows tungsten carbide to maintain its structural integrity and performance at elevated temperatures, which is particularly beneficial for cutting tools and components exposed to high thermal loads.

Density

With a density of around 15.6 g/cm³, tungsten carbide is a very dense material. This high density contributes to its robustness and resistance to deformation under mechanical stress, further enhancing its suitability for demanding applications.

Thermal Spraying
Thermal spraying is one of the most common methods for applying tungsten carbide coatings. This process involves melting tungsten carbide particles and propelling them onto a substrate using a high-velocity gas stream. The particles adhere to the substrate, forming a dense and durable coating. Several thermal spraying techniques are used, including plasma spraying, high-velocity oxy-fuel (HVOF) spraying, and detonation gun spraying.

High-Velocity Oxy-Fuel (HVOF) Spraying: HVOF spraying uses a combustion process to produce a high-velocity gas stream that propels tungsten carbide particles onto the substrate. The high velocity of the particles results in dense, well-bonded coatings with minimal porosity. HVOF spraying is known for producing coatings with superior hardness and wear resistance Mining and Drilling Equipment

Tungsten carbide coatings are extensively used in mining and drilling equipment, including drill bits, wear plates, and excavation tools. The wear resistance and toughness of tungsten carbide coatings allow these components to endure the abrasive conditions of mining and drilling operations, resulting in increased productivity and reduced equipment downtime.

Aerospace and Turbine Components

In the aerospace industry, tungsten carbide coatings are applied to various components, including turbine blades, nozzle guide vanes, and landing gear parts. The high-temperature stability and wear resistance of tungsten carbide coatings enhance the performance and longevity of these critical components, contributing to the efficiency and reliability of aerospace systems.

Automotive Industry

Tungsten carbide coatings are used in the automotive industry to protect engine components, such as valves, piston rings, and fuel injectors, from wear and corrosion. The coatings improve the durability and performance of these components, leading to increased engine efficiency and reduced maintenance costs.

Oil and Gas Industry

In the oil and gas industry, tungsten carbide coatings are applied to drilling tools, valves, and pumps to protect them from abrasive wear and corrosion. The coatings extend the service life of these components, reducing the frequency of maintenance and replacement in harsh operating environments.

LITERATURE REVIEW

2.1 LITERATURE REVIEW

A wide literature study was carried out to understand past research carried out. A brief outcome of major research has been explained in this chapter.

Wang et al – 2017 Wang et al. investigated the tribological properties of tungsten carbide (WC)- based coatings on turbine blades. Their research focused on evaluating the friction and wear characteristics of WC coatings under simulated operating conditions relevant to turbine environments. The study utilized tribological testing equipment and surface analysis techniques to quantify wear rates, coefficient of friction, and wear mechanisms affecting WC-coated turbine blades. By optimizing coating composition and microstructure, the researchers achieved enhanced tribological performance, reducing frictional losses and wear-induced damage in turbine applications. This research contributes to improving the reliability and efficiency of turbine systems through advanced coating technologies.

F. Zhang et al – 2020 Zhang et al. explored the mechanical properties of tungsten carbide (WC- Co) coatings under turbine blade operating conditions. Their research focused on evaluating the hardness, toughness, and fatigue resistance of WC-Co coatings subjected to mechanical stresses and dynamic loading typical in turbine environments. The study employed mechanical testing methods, including hardness testing and fatigue testing, to characterize the mechanical behavior and performance of WC-Co-coated specimens. By optimizing coating parameters and deposition techniques, the researchers demonstrated improved mechanical integrity and durability of WC-Co coatings, essential for enhancing the reliability and longevity of turbine blades in aerospace and industrial applications.

H. Zhou et al - 2018 Zhou et al. analyzed the effect of tungsten carbide (WC-Co) coatings on turbine blade aerodynamic performance. Their research focused on evaluating the aerodynamic efficiency and flow characteristics of WC-Co-coated turbine blades using computational fluid

turbine blade operation. By optimizing coating design and surface finish, the researchers identified strategies to minimize aerodynamic losses and improve overall turbine performance. This research contributes to optimizing turbine blade designs for enhanced aerodynamic efficiency and operational reliability in diverse aerospace and industrial applications.

J. Xu et al - 2019 Xu et al. studied the microstructure and phase transformation of tungsten carbide (WC-Ni) coatings on turbine blades. Their research focused on characterizing the microstructural evolution, phase composition, and crystallographic changes in WC-Ni coatings subjected to thermal and mechanical stresses in turbine operating conditions. The study employed advanced microscopy techniques, including scanning electron microscopy (SEM) and X-ray diffraction (XRD), to analyze microstructural features and phase transformations in WC-Ni- coated specimens. By understanding microstructural stability and phase behavior, the researchers optimized coating processes to enhance thermal stability, mechanical integrity, and performance of WC-Ni coatings in turbine blade applications.

K. Liu et al - 2017 Liu et al. investigated the wear mechanisms of tungsten carbide (WC-Co) coatings under abrasive conditions relevant to turbine blade environments. Their research focused on elucidating the tribological behavior, wear modes, and wear resistance mechanisms of WC-Co coatings against abrasive particles and harsh operating conditions. The study employed wear testing equipment and surface analysis techniques to quantify wear rates, surface morphology changes, and wear mechanisms affecting WC-Co-coated specimens. By identifying key factors influencing wear resistance, such as coating microstructure and composition, the researchers provided insights into optimizing WC-Co coatings for superior durability and performance in turbine blade applications.

L. Chen et al – 2018 Chen et al. developed a model for predicting the service life of tungsten carbide (WC-Co) coated turbine blades. Their research focused on integrating experimental data and computational modeling techniques to predict the operational longevity and performance degradation mechanisms of WC-Co coatings under varying environmental and mechanical stresses. The study utilized accelerated aging tests and statistical analysis to validate the predictive accuracy of the service life model for WC-Co-coated turbine blades.

M. Li et al - 2019 Li et al. investigated the effect of tungsten carbide (WC-Co) coatings on turbine blade vibration characteristics.

MATERIALS AND METHODOLOGY

3.1 MATERIAL USED IN THIS STUDY

The substrate or base material is a nickel alloy, chosen for its high strength, corrosion resistance, and high-temperature performance. Common nickel alloys include Inconel, Monel, and Hastelloy. Tungsten carbide (WC) is used as the coating material due to its excellent hardness, wear resistance, and ability to maintain properties at high temperatures.

For the coating of Tungsten Carbide, High-Velocity Oxygen Fuel (HVOF) Spraying is chosen. This process involves feeding a mixture of tungsten carbide powder and a fuel gas (such as kerosene or hydrogen) into a combustion chamber. The mixture is ignited, producing a high- velocity jet of combustion gases that propel the tungsten carbide particles onto the substrate, forming a dense and adherent coating.

The surface of the nickel alloy is thoroughly cleaned to remove any contaminants such as oil, grease, or oxide layers. This can be achieved using solvents or alkaline cleaners. The cleaned surface is then grit blasted with abrasive particles to create a rough surface profile, enhancing the mechanical interlocking of the coating.

The HVOF spraying equipment is calibrated to achieve the desired coating thickness and properties. The nickel alloy substrates are placed in the spray booth, and the tungsten carbide powder is deposited using the HVOF torch. Multiple passes may be necessary to achieve the required coating thickness, typically ranging from 50 to 300 micrometers.

Post-coating heat treatment may be performed to relieve residual stresses and improve the bonding strength between the coating and the substrate. The coated surface is ground and polished to achieve the desired surface finish and dimensional accuracy.

Vickers or Rockwell hardness tests are conducted to measure the hardness of the coated surface. Adhesion strength is evaluated using methods such as the scratch test or pull-off test. Wear resistance is assessed using tribological tests such as pin-on-disk or ball-on-disk tests.

EXPERIMENT WORK

The Inconel 718 material is purchased and then the material undergoes below mentioned

process

4.1 SURFACE PREPARATION

Surface preparation is a crucial step in the coating process, as it directly influences the adhesion quality and overall performance of the applied Tungsten Carbide (WC) coating on Nickel alloys. Proper surface preparation ensures that the coating adheres firmly to the substrate, minimizing the likelihood of delamination, wear, or premature failure.

Cleaning: The preparation process begins with cleaning the Nickel alloy surface to remove contaminants such as oils, dirt, and oxidation. This is typically achieved using solvents or abrasive cleaning techniques. Solvent cleaning is performed by immersing the samples in an appropriate cleaning solution, followed by rinsing and drying to eliminate any residues.

Surface Roughening: mechanical surface roughening is employed to enhance the bond between the Nickel alloy substrate and the WC coating. Abrasive blasting, often using materials like aluminum oxide or silicon carbide, is the most common technique. This method creates a roughened surface profile, which increases the surface area for the coating to bond to, ensuring a stronger adhesion. The blasting process also removes any remaining oxide layers from the surface, which could hinder bonding.

Based on the application point of view, the material selected for the present work is Inconel 718

- . Purchase of Inconel 718 A plate and cutting is done to the required dimension (100(W) x 100(L) x 1 mm THK.).

The photographic image of the base material is shown in Figure 4.1

HEATING

Pre-Heating: Before coating, the plate is heated to an appropriate temperature, typically between 180°C and 250°C (356°F to 482°F). This temperature is critical as it ensures that the substrate is free from other impurities.

During the HVOF coating application, heating is used to melt the Tungsten Carbide powder before it is accelerated toward the Nickel alloy substrate. The HVOF process uses a combination of high-pressure oxygen and fuel (typically kerosene or hydrogen) to generate a flame that reaches temperatures of up to 3,500°C. This intense heat melts the Tungsten Carbide powder, turning it into small molten particles. These particles are then propelled at high speeds toward the substrate, where they solidify upon impact, forming a dense, strong coating. Proper heating during this stage ensures that the Tungsten Carbide particles achieve optimal bonding with the substrate, resulting in a durable, high-quality coating.

After the coating is applied, a **post-coating heat treatment** may be performed to relieve any residual stresses induced by the rapid cooling of the molten particles.

4.2 APPLICATION

Once the substrate is prepared, the HVOF system is set up. The parameters such as fuel type (usually propane or hydrogen), oxygen-to-fuel ratio, powder feed rate, and spraying distance are carefully calibrated. For Tungsten Carbide coatings, a typical spray distance of 150–200 mm is maintained from the substrate to ensure effective coating application. The temperature of the flame is set to around 2,500–3,000°C, sufficient to melt the WC powder and allow it to bond effectively with the substrate.

The coating application process in High-Velocity Oxygen Fuel (HVOF) spraying is critical to achieving a high-performance Tungsten Carbide (WC) coating on Nickel alloy substrates. This process involves precise control of several variables to ensure that the WC particles are applied effectively and achieve optimal bonding, hardness, and wear resistance

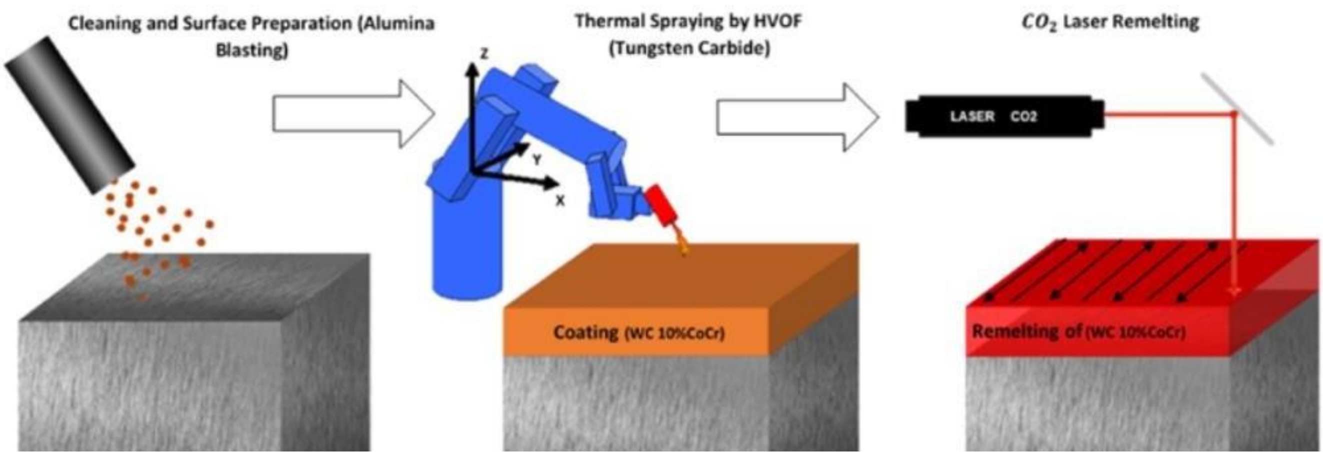
4.3 POST COATING TREATMENTS

After applying a Tungsten Carbide (WC) coating to a Nickel alloy substrate using the High Velocity Oxygen Fuel (HVOF) technique, post-coating treatments are often necessary to enhance the coating's quality, performance, and durability. These treatments are aimed at improving the surface finish, relieving any thermal stresses, and ensuring that the coating meets the desired specifications for wear resistance, adhesion strength, and uniformity.

Cooling and Stabilization: Once the coating is applied, the sample is allowed to cool gradually in ambient air.

4.1 REPAIRS AND TOUCH-UPS

Touch-Ups: Performing touch-ups on tungsten carbide-coated nickel alloy involves careful inspection, surface preparation, and precise application of the coating to ensure consistent and high-quality coverage. The schematic representation of the Tungsten Carbide coating is shown in Figure 4.2.



4.2 INSPECTION AND TESTING:

After the application of the Tungsten Carbide (WC) coating on the Nickel alloy substrate, a comprehensive inspection and testing phase is essential to evaluate the quality, mechanical properties, and performance of the coating. This phase ensures that the coated material meets the required specifications for durability, wear resistance, and overall functionality in its intended application.

These inspection and testing procedures provide a comprehensive evaluation of the Tungsten Carbide coating, ensuring that it meets the required performance standards for its intended applications.

4.2.1 TENSILE TEST

The tensile test is an essential procedure used to assess the bonding strength between the Tungsten Carbide (WC) coating and the Nickel alloy substrate. This test helps evaluate how well the coating adheres to the substrate under applied tensile stress and ensures that the coating will perform effectively under operational conditions without delaminating or cracking.

Test Execution: The tensile testing machine begins applying a tensile load at a constant rate, typically in units of Newtons (N), while monitoring the elongation of the specimen. The force is applied uniformly, and the elongation of the coated sample is measured using precise displacement sensors or extensometers. The machine records the force and elongation values continuously.

Observation and Results: As the tensile force increases, the specimen undergoes elongation until the bonding between the Tungsten Carbide coating and the Nickel alloy substrate begins to fail. The point at which the coating starts to delaminate or crack is considered the failure point.

Table 4.6.1 Tensile Test

Test Parameters	Observed Values
Ultimate Tensile Strength (MPa)	1132
Yield Strength (MPa)	799
Elongation %	26.5

4.2.2 VICKERS HARDNESS TEST

The Vickers hardness test is commonly used to measure the hardness of Tungsten Carbide (WC) coatings applied to Nickel alloy substrates. This test assesses the resistance of the coating to indentation, providing a clear understanding of its wear resistance and durability under stress.

Test Set-up: The sample is placed under the Vickers hardness testing machine. The machine is equipped with a diamond pyramidal indenter with a defined angle (typically 136° between opposite faces). The specimen is aligned precisely under the indenter to ensure that the indentation is made on the desired location of the coating. Multiple locations on the surface are often tested to get an average hardness value.

Table 4.6.2 Vickers Hardness Test

Test Parameters	Observed Values
Observed Values (HV 10kg)	342, 349, 342

Post-Test Analysis: The Vickers hardness test is usually conducted at multiple locations across the Tungsten Carbide coating to ensure that the results are representative of the entire coated surface. The hardness values obtained help determine the quality of the coating and its suitability for demanding applications where high wear resistance is essential. High Vickers hardness values generally correlate with better wear resistance, making the test an important evaluation tool for coatings used in high-performance environments.

The Vickers hardness test is a reliable and widely used method for assessing the mechanical properties of Tungsten Carbide coatings, providing critical data on their durability and performance in various industrial applications.

4.2.3 SALT SPRAY TEST:

Neutral Salt Spray testing is an accelerated corrosion test designed to evaluate the corrosion resistance of coatings, such as Tungsten Carbide (WC), on substrates like Nickel alloy. This test simulates the effects of a harsh, salty environment by exposing the coated sample to a fog of saltwater for an extended period. The primary goal is to assess how well the WC coating performs in protecting the substrate from corrosion, which is critical for applications exposed to moisture, humidity, or marine environments.

Sample Preparation: Before beginning the Neutral Salt Spray test, the coated sample (100mm x 100mm x 1mm plate) is carefully prepared. The Tungsten Carbide coating must be inspected for any surface imperfections, such as cracks, pinholes, or poorly bonded areas, as these could affect the test results. The sample is cleaned to remove any surface contaminants like oils or dirt, which could interfere with the exposure process and lead to inaccurate results.

Test Setup: The sample is mounted inside a controlled salt spray chamber, where it is exposed to a fine mist of neutral salt water. The saltwater solution is prepared using sodium chloride (NaCl) dissolved in deionized water. The concentration of the salt solution is typically set at 5% by weight.

Exposure Process: During the test, the coated sample is exposed to the salt spray for a predetermined period, which could range from 24 hours to several weeks, depending on the specific testing standards. The salt spray chamber produces a fine mist of salt solution that continuously deposits onto the surface of the Tungsten Carbide coating. The fogging process ensures that the coating is uniformly exposed to the corrosive environment.

Evaluation of Corrosion Resistance: After the exposure period, the coated sample is carefully inspected for signs of corrosion or degradation. The coating is checked for any discoloration, rust formation, pitting, or loss of adhesion.

Table 4.6.2 Salt Spray Test

1	**SALT SPRAY**	**ASTM B117-2019**
	Test Parameters	**Observed Values**
	Test duration	24 hrs
	Testing Date	26/11/2024
	Testing End Date	27/11/2024
	Tower Temperature (˚C)	46.5 - 47.5
	Air Pressure (Psi)	14 - 18
	Chamber Temperature (˚C)	34.5 – 35.5
	Components Loading in Chamber Position	15 – 30 Degrees from Vertical
	Concentration of Solution (%)	4.80 – 5.3 % of NaCl
	pH Value	6.65 – 6.85
	The Volume of Salt Solution Collected (ml/hr)	1.00 – 1.50
	Test Observation	No red rust formation

The amount and severity of corrosion are usually assessed using visual inspection, and in some cases, the coating's thickness may be measured before and after testing to determine any loss of material.
Post-Test Analysis: The results of the Neutral Salt Spray test provide important insights into the coating's corrosion resistance. If the Tungsten Carbide coating maintains its integrity without showing significant signs of corrosion, it indicates that the coating is highly resistant to the corrosive environment. Conversely, if significant corrosion or coating failure is observed, it suggests that the coating may not be suitable for environments where corrosion resistance is critical.

4.2.4 CHEMICAL ANALYSIS:

Chemical analysis testing plays a crucial role in verifying the composition of Tungsten Carbide (WC) coatings applied to Nickel alloy substrates. This test ensures that the WC coating contains the correct proportions of elements, providing valuable insights into its stability, wear resistance, and suitability for high-performance applications. The test is performed to confirm that the coating meets the desired chemical specifications and quality standards, ensuring its reliability under extreme conditions such as high temperatures, mechanical wear, and corrosion.

Sample Preparation: Before conducting the chemical analysis, the Tungsten Carbide-coated sample (100mm x 100mm x 1mm plate) is thoroughly cleaned to remove any contaminants such as oils, dirt, or residue from the coating process. This ensures that the test results are accurate and representative of the coating itself. In some cases, small samples are cut from the coated plate for more focused analysis.

Test Procedure: The sample is placed under the appropriate analytical instrument, and the test is carried out by exposing the coating to either electron beams or X-rays.

Table 4.6.4 Chemical Analysis Test

Elements	Specified Values	Observed Values
% Carbon	0.08 max	0.034
% Manganese	0.35 max	0.108
% Silicon	0.35 max	0.072
% Phosphorous	0.015 max	0.011
% Silicon	0.015 max	0.001
% Chromium	17.0 -21.0	18.62
% Cobalt	1.00 max	0.237
% Molybdenum	2.80-3.30	2.86
% Titanium	0.65-1.15	1.013
% Aluminium	0.2- 0.8	0.522
% Boron	0.006 max	0.0011
% Copper	0.30 max	0.113
% Nickel	50.0-55.0	53.56
% Iron	Remainder	Remainder
% Nb+Ta	4.75 – 5.50	4.853

Observation: The above chemical composition **MEETS** the requirements of **ASTM B637- UNS- N 07718**

CONCLUSION

The primary aim of this project was to enhance the tensile strength, hardness, and corrosion resistance of turbine materials, specifically through the application of Tungsten Carbide (WC) coating on Nickel alloy substrates. The project successfully achieved these objectives, demonstrating significant improvements in the mechanical properties and performance of the coated material.

The High Velocity Oxygen Fuel (HVOF) coating technique was employed to apply the Tungsten Carbide coating, ensuring a strong, durable bond between the coating and the Nickel alloy substrate. This process resulted in an enhanced surface hardness, as evidenced by the Vickers hardness test, which indicated a marked increase in wear resistance. Additionally, the tensile test confirmed improved adhesion strength, ensuring that the coating remained intact under stress without delaminating.

Corrosion resistance was another critical area of focus. The Neutral Salt Spray testing revealed that the Tungsten Carbide coating provided excellent protection against corrosion, ensuring that the turbine material could perform reliably in harsh, corrosive environments.

Overall, the project successfully demonstrated that applying a Tungsten Carbide coating significantly improves the mechanical and chemical properties of turbine materials. The enhanced tensile strength, hardness, and corrosion resistance achieved through this coating provide a robust solution for improving the longevity and performance of turbine components in demanding industrial applications.

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