UNIVERSITI MALAYSIA KELANTAN

COMPARISON OF ADHESION PROPERTIES ALUMINIUM, STAINLESS STEEL AND MILD STEEL SUBSTRATE COATED WITH METALLIC CERIUM

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A thesis submitted in fulfilment of the requirements for the degree of Bachelor of Applied Science (Materials Technology) with Honours

FACULTY OF BIOENGINEERING AND TECHNOLOGY
UMK

2024

DECLARATION

I declare that this thesis entitled Comparison of Adhesion Properties Aluminium, Stainless Steel And Mild Steel Substrate Coated With Metallic Cerium is the results of my own research except as cited in the references.

Signature : ______________________________

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Supervisor's Name : ______________________________

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Date : ______________________________

ACKNOWLEDGEMENT

Bissmillahirrahmanirrahim,

Alhamdulillah, Thanks to Allah S.W.T for His guidance and showers of blessing that permits me to conduct this Final Year Project (FYP) which is title Comparison Of Adhesion Properties Aluminium, Stainless Steel And Mild Steel Substrate Coated With Metallic Cerium. I would like to express my sincere gratitude to all those who have contributed to the completion of this thesis. Their support and assistance have been invaluable throughout the journey.

First and foremost, I extend my deepest appreciation to my supervisor, Ts. Dr. Teo Pao Ter for his unwavering guidance, insightful feedback, and continuous encouragement. His expertise has greatly enriched the quality of this thesis.

I am also thankful to lab assistants of University Malaysia Kelantan for their helping and guiding me with the lab works and analysis machines usage, which significantly enhanced the overall outcome. I also would like to thank all laboratory assistant involved for guiding me with the test conducted. Special thanks go to University Malaysia Kelantan for providing financial support, resources and facilities, without them, this research would not have been possible. I want to acknowledge the support of my friends and family for their understanding, encouragement, and patience during the various phases of this endeavour.

Lastly, I appreciate the collective efforts of everyone who has played a role, no matter how big or small, in the successful completion of this thesis. Your contributions have been instrumental and are genuinely appreciated.

Comparison of Adhesion Properties Aluminium, Stainless Steel and Mild Steel Substrate Coated with Metallic Cerium

ABSTRACT

Organic coatings, while initially protective, degrade over time due to environmental exposure, needing periodic reapplication and possibly containing harmful substances. Cerium conversion coatings, on the other hand, provide a greener and safer option that adheres strongly to metals such as aluminium, magnesium, and zinc, improving corrosion resistance and durability. The purpose of this study is to evaluate the adhesion qualities of metallic cerium coatings on substrates such as aluminium, stainless steel, and mild steel. Surface preparation procedures specific to each substrate were used, and adhesion strength was measured using established methods. X-ray fluorescence (XRF) investigation aided in the identification of certain alloy types. The experimental design and data analysis used ANOVA to determine the significant effect of substrates on adhesion strength. The results show that cerium coatings have the potential to improve adhesion and performance in a wide range of industrial applications. This study provides important insights into optimising coating processes and increasing material durability.

Perbandingan Sifat Penyatu Cerium Logam pada Substrat Aluminium, Keluli Tahan Karat, dan Keluli Lembut

ABSTRAK

Salutan organik, walaupun pada permulaannya adalah perlindungan, merosakkan dari semasa ke semasa disebabkan oleh pendedahan kepada persekitaran, memerlukan penyemperitan berkala dan mungkin mengandungi bahan berbahaya. Salutan penukaran cerium, sebaliknya, menyediakan pilihan yang lebih hijau dan lebih selamat yang melekat kuat pada logam seperti aluminium, magnesium, dan zink, meningkatkan ketahanan korosi dan kebolehgunaan. Tujuan kajian ini adalah untuk menilai kualiti penyatuan salutan cerium logam pada substrat seperti aluminium, keluli tahan karat, dan keluli lembut. Prosedur persediaan permukaan yang khusus untuk setiap substrat digunakan, dan kekuatan penyatuan diukur menggunakan kaedah yang telah ditetapkan. Penyiasatan sinar-X fluoresens (XRF) membantu dalam pengenalpastian jenis aloi tertentu. Reka bentuk eksperimen dan analisis data menggunakan ANOVA untuk menentukan kesan signifikan substrat terhadap kekuatan penyatuan. Hasil kajian menunjukkan bahawa salutan cerium mempunyai potensi untuk meningkatkan penyatuan dan prestasi dalam pelbagai aplikasi industri. Kajian ini memberikan pandangan penting dalam mengoptimumkan proses penyalutan dan meningkatkan kebolehgunaan bahan.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Various metals, including aluminium and mild steel, are strategically mixed with other elements to enhance their properties for specific applications. Aluminium, commonly used in airplane construction, household items, and electrical wires, undergoes alloying with metals like silicon for improved performance. Mild steel finds widespread use in automotive, furniture, and construction industries due to its versatility and durability. Stainless steel, containing over 10.5% chromium, forms a protective passive layer against corrosion, making it suitable for applications such as washing drums, automotive components, and medical technology. The corrosion behaviour of aluminium, influenced by its naturally formed film, can be managed by controlling the solution conditions, with chlorides hindering film repair and promoting rapid corrosion. The overall significance lies in the diverse applications and adaptability of these materials, each playing a crucial role in different industries.

Stainless steels are popular due to their ability to resist corrosion, but they can still suffer from pitting corrosion, where small areas of the metal break down in specific harsh environments. This kind of corrosion, even though it's not widespread, can be really damaging and often causes structures to fail. This research suggests that how materials are made can influence how likely they are to corrode, and this new information can help make those materials even better in the future (Kumaran et al., 2021).

Mild steel isn't usually picked for its ability to resist corrosion; it's more about its strength, how easy it is to work with, and its affordability. Generally, it's better to avoid acids with mild steel. Mild steel doesn't resist corrosion well because it's easy for cathodic reduction to occur on its surface, and the layer formed when it corrodes isn't solid and sticks poorly. People use mild steel a lot because it's cheap, has decent strength, and is easy to work with. In places like industrial settings where there's moisture and chemicals in the air, it's more likely to corrode because the conditions are harsher.

Aluminum, mild steel, and stainless steel are frequently utilized metals in manufacturing. Aluminum, valued for its lightweight, conductivity, and corrosion resistance, is well-suited for electrical purposes. Mild steel, recognized for its strength and durability, is susceptible to rust and corrosion. Stainless steel, distinguished by its exceptional resistance to corrosion and staining, is ideal for applications prioritizing hygiene and longevity. According to Policastro et al. (2021), combining aluminum and stainless steel poses a risk of galvanic corrosion, but this can be alleviated through the use of isolating coatings or insulating washers. The selection between aluminum and stainless-steel hinges on factors such as composition, mechanical properties, and cost, with aluminum being favored for electrical applications and stainless steel for scenarios emphasizing hygiene and durability.

The corrosion of aluminum, mild steel, and stainless steel can be a concern, especially when these metals come into contact with each other. Galvanic corrosion can occur when two electrochemically dissimilar metals are in contact, in the presence of an electrolyte, and there is an electrical connection between them (Policastro et al., 2021). This can lead to the deterioration of the metals at the points of contact. For example, when aluminum comes into contact with stainless steel, or mild steel, galvanic corrosion can occur, particularly in environments such as marine settings or in the presence of saltwater or other conductive media. To mitigate this, isolating coatings, insulating washers, or using one material to fabricate electrically isolated systems or components can be employed to prevent galvanic corrosion. The relative surface area of the metals in contact also plays a role in the severity of the corrosion. Therefore, it's important to consider the specific application and environmental conditions when choosing and using these metals together.

Aluminium is typically protected from corrosion by procedures such as anodizing, which creates a protective oxide layer, as well as the application of protective coatings or paint. Mild steel, which is prone to rust, is frequently galvanised by depositing a zinc layer to prevent rust, which is supplemented by the use of corrosion-resistant coatings. Stainless steel, which is naturally resistant to corrosion, may require passivation a technique that promotes the creation of a passive oxide layer to increase its corrosion resistance.

Coating materials provide a wide range of benefits in a variety of industrial applications. Coatings primarily function as a protective barrier, sheltering substrates from environmental hazards such as corrosion, abrasion, and chemical exposure. They also help to the resilience and lifetime of materials, reducing wear and tear. Furthermore, coatings frequently have special functional features, such as thermal insulation or electrical conductivity, which improve the performance of coated surfaces. In terms of aesthetics, coatings can impart desired colours, textures, or finishes, responding to both functional and visual needs. These characteristics highlight the critical role coatings play in strengthening materials and improving their overall functioning.

1.2 Problem Statement

Organic coating, while effective in many ways, do have their drawbacks. One significant disadvantage is their susceptibility to wear and tear over time. Despite providing initial protection, these coatings can degrade due to exposure to environmental factors like sunlight, moisture, and chemicals. This deterioration might lead to the need for frequent reapplication or maintenance, which can be both time-consuming and costly. Additionally, some traditional coatings may contain volatile organic compounds (VOCs) or hazardous chemicals, posing potential health and environmental risks during application and disposal.

Cerium conversion coating emerges as a superior solution in the dynamic landscape of surface protection, presenting a multitude of advantages over organic coating methodologies. In stark contrast to antiquated chromate-based coatings fraught with environmental concerns, cerium offers a greener and safer alternative without compromising its efficacy in safeguarding metals. Noteworthy is cerium's exceptional adhesion to metals such as aluminum, magnesium, and zinc, establishing robust bonds that endure under challenging conditions.

Metallic cerium has its own adhesion strength. Adhesion strength is important for cerium coating of aluminum, mild steel, and stainless steel because it determines the ability of the coating to adhere to the substrate and resist detachment or peeling (Tang et al., 2011). The adhesion strength of the coating is critical for its performance in enhancing the corrosion resistance and durability of the metal substrates. Additionally, a study on the influence of aluminum could improve the adhesion between the substrates and the coating.

The aim of this study is to assess the adhesion properties exhibited by metallic cerium coatings when applied to aluminium, stainless steel, and mild steel substrates. This investigation aims to explain on the variations in adhesion strength across these three substrates. By conducting comparative analyses, the study seeks to discern and comprehend the differences in the adhesion strength demonstrated by cerium coatings on these substrates: aluminium, stainless steel, and mild steel.

1.3 Objectives

The primary objective of this study is to investigate and compare the adhesion properties of metallic cerium coatings on aluminum, stainless steel, and mild steel substrates. Specific research goals include:

- To prepare cerium coating on aluminium, stainless steel and mild steel using chemical conversion method.
- To correlate the adhesion strength with the types of metal substrate

1.4 Scope of Study

This study is designed to comprehensively investigate and compare the adhesion properties of metallic cerium coatings on three diverse substrate materials: aluminum, stainless steel, and mild steel. The scope of this research encompasses a systematic analysis of various critical aspects related to adhesion, aiming to provide valuable insights into the performance and applicability of cerium coatings in different industrial settings. The primary components of the study include surface preparation techniques tailored to each substrate, adhesion testing utilizing standard methodologies, evaluation of the durability of cerium coatings when exposed to environmental and mechanical stresses, identification of optimal conditions for strong adhesion, and a comparative analysis of the adhesion characteristics between the three substrates. The study acknowledges its limitations, specifically its focus on these specific substrates and the exclusion of other materials, as well as the omission of in-depth industrial application assessments. The research will be conducted within a defined time frame to ensure efficient completion of sample preparation, testing, data analysis, and reporting of results. Overall, this study aims to contribute to our understanding of how metallic cerium coatings can enhance adhesion and improve the performance of materials in a variety of industrial applications.

1.5 Significance of The Study

The choice of substrate material is a critical factor in determining the overall performance of coatings. Aluminum, stainless steel, and mild steel are widely used in various industries for their unique properties and cost-effectiveness. The successful adhesion of metallic cerium to these substrates can significantly impact the performance, longevity, and maintenance requirements of products and structures.

Aluminum is lightweight and possesses excellent corrosion resistance, making it a preferred choice in aerospace and transportation industries. Achieving strong adhesion of metallic cerium to aluminum surfaces can improve the corrosion resistance and durability of components in these applications.

Stainless steel is known for its corrosion resistance and mechanical strength. It is commonly used in applications where hygiene and durability are essential, such as the food industry and medical equipment. The adhesion of cerium coatings to stainless steel can enhance these properties.

Mild steel is an economical choice for structural and industrial applications. Improving the adhesion of metallic cerium to mild steel can extend the lifespan of infrastructure and reduce maintenance costs.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Stainless steel, mild steel, and aluminium are all commonly utilised materials, with each bringing unique characteristics to a variety of applications. Stainless steel, famed for its corrosion resistance, takes on the role of a staunch guardian, assuring endurance across a range of functions from building washing drums to producing components in automotive and medical technology. This durable alloy demonstrates the importance of corrosion-resistant materials in increasing the lifetime and functioning of a wide range of items (Pfeifer, 2022).

Mild steel is widely used in building and manufacturing because to its durability and applicability in many sectors. Mild steel serves as a core element supporting the stability and strength of numerous applications, from erecting buildings and fashioning furniture to strengthening structures with its solid presence. Its versatility and mechanical qualities make it a standard in engineering and construction, providing a solid basis for a wide range of buildings (Pfeifer, 2022).

Meanwhile, according to L et al., (2012), aluminium is effectively through the aerospace sector, contributing to domestic basic needs, and playing a crucial role in electrical and chemical applications. This versatile metal, known for its low density and strong strength, finds applications in aircraft design, daily home objects, and important components such as electrical lines. The secret is in its capacity to combine strength with lightness, making it a useful resource in a variety of technical developments and everyday comforts. Stainless steel, mild steel, and aluminium provide the foundation of many applications, illustrating the wide and important roles that materials play in creating our everyday lives.

Stainless steel, mild steel, and aluminum are three common metals with a wide variety of uses. Stainless steel is known for its corrosion resistance and is used in applications like washing drums, automotive components, and medical technologies. Mild steel is strong and affordable, making it a popular choice for construction, furniture, and reinforcement. Aluminum is lightweight and strong, making it ideal for aircraft construction, kitchenware, electrical cables, and chemical applications.

All three metals can corrode, however. Stainless steel can be damaged by pitting corrosion in harsh environments. Mild steel is susceptible to rust, especially in cold or corrosive conditions. Aluminum can corrode in the presence of chlorides or other harsh substances. To protect these metals from corrosion, it is important to consider the environment in which they will be used and take appropriate precautions.

2.2.1 Corrosion Issue of Metal

Metals have specific properties that impact their usefulness for various uses. Aluminium has a natural corrosion resistance mechanism that involves the creation of a thin oxide coating (L et al., 2012). This feature makes it an excellent choice for a variety of applications, including construction materials and marine equipment. Recognising its fragility in severe settings, aluminium strengthens its protection with additional coatings such as anodizing and paint, adding another layer of resistance to the elements.

Stainless steel relies on inner strength, which is generated from components such as chromium and nickel. These components react with oxygen to generate a self-healing oxide layer that continuously protects itself against corrosion. This outstanding quality makes stainless steel ideal for applications requiring high cleanliness standards, such as kitchen equipment and medical devices. Despite its outstanding strength, stainless steel is not impervious, especially in strongly acidic or chloride-rich environments. To counteract this susceptibility, particular kinds of stainless steel are used, or extra preventive measures, such as passivation methods, are applied to assure long-term durability.

Mild steel, on the other hand, is used extensively in building and infrastructure projects because to its low cost and durability. However, its sensitivity to corrosion offers a difficulty. To overcome this constraint, mild steel uses exterior coatings such as galvanization and paint to function as both a shield and a sword. Furthermore, for big constructions such as bridges and pipelines, a strategic technique known as cathodic protection is used, in which a sacrificial metal corrodes instead of the mild steel, increasing its longevity in harsh conditions. Each of these metals, with its own strengths and weaknesses, highlights the delicate balance between material qualities and the requirements of certain applications.

2.2.2 Common Method of Corrosion Protection: Organic Painting

Organic paint emerges as a sustainable and effective protector for aluminium, stainless steel, and mild steel. Unlike typical coatings, organic paint compositions prioritise environmentally benign components, minimising the impact on ecosystems. Organic paint protects aluminium, a lightweight champion prone to corrosion, by generating a protective coating that protects against moisture, oxidation, and other harmful substances (Veleva, 2012). This technology not only improves the longevity of aluminium applications, but also connects with the rising need for sustainable practices in numerous industries.

Organic paint contains chromium and nickel, which strengthens the corrosion resistance of stainless steel. The chromium and nickel components found in stainless steel react with oxygen, generating a strong oxide coating. Organic paint adds an extra layer of protection to stainless steel, keeping it shiny and corrosion-resistant in a variety of situations. This combination proved particularly helpful in applications that need both endurance and a visually pleasing finish.

Mild steel, a cheap and strong material used in construction, presents issues due to its corrosive nature. Based on Veleva, (2012), organic paint is a low-cost and environmentally responsible alternative for providing a protective covering that covers mild steel from the weather. This strategy boosts the material's lifetime and broadens its usability in diverse infrastructure projects, contributing to sustainable building practices. In essence, the use of organic paint protection represents a step towards ecologically aware metal preservation, providing a harmonic combination of effective corrosion resistance and ecological responsibility for aluminium, stainless steel, and mild steel applications.

2.2.3 Limitation of Organic Coating

Despite the many approaches for reducing corrosion, there are basic limits that prohibit corrosion from being completely eliminated. These limits are due to the fundamental nature of corrosion as an electrochemical process, the complexity of material characteristics and environmental conditions, and the cost of applying corrosion control techniques. One fundamental constraint of corrosion control is that corrosion is an electrochemical process, which happens when a metal interacts with its surroundings. This reactivity cannot be entirely eliminated since it is an inherent feature of metals. As a result, corrosion management measures focus on regulating and reducing the rate of corrosion rather than removing it completely (L et al., 2012). Material qualities have an important function in minimising corrosion control. The susceptibility of a material to corrosion is determined by its composition, microstructure, and surface state. While protective coatings and treatments can improve corrosion resistance, they cannot totally eliminate a material's natural susceptibility to corrosion.

Environmental considerations also hinder corrosion control. The corrosivity of the environment, as determined by temperature, humidity, and the presence of corrosive substances, can have a considerable impact on the success of corrosion management techniques. Complete protection in severely corrosive conditions may be impracticable or economically unfeasible. Economic concerns may help to restrict corrosion control. Implementing corrosion control techniques, such as applying protective coatings or utilising corrosion-resistant materials, incurs expenses that must be weighed against the possible economic losses caused by corrosion. In some circumstances, the expense of comprehensive corrosion avoidance may outweigh any possible advantages. Despite these limitations, corrosion management is nevertheless an important method for safeguarding infrastructure, machinery, and other assets from deterioration. Engineers and scientists may efficiently manage corrosion and extend the life of precious materials by knowing their limitations and implementing suitable corrosion control techniques.

Organic paints, while widely utilised for their great protective and aesthetic properties, have limitations, prompting scientists to investigate other alternatives such as cerium conversion coatings. One noteworthy obstacle is adhesion failure, which occurs on metals such as stainless steel with a passive oxide layer, resulting in flaking and weakened protection. Cerium conversion coatings solve this by making the surface more responsive to organic paints, which may improve bond strength (Zhoying He, n.d.). Furthermore, environmental worries about volatile organic compounds (VOCs) in conventional organic paints have prompted the study of cerium coatings, which are noted for their water-based composition and eco-friendliness. High-temperature applications provide another barrier for organic paints, making cerium conversion coatings, which have improved durability at high temperatures, an attractive option for conditions such as engine components. The amazing self-healing capabilities of cerium coatings, which outperform some organic paints, provide an extra benefit in sustaining long-term protection without the need for repeated repaints. Finally, aesthetic considerations are important, since cerium conversion coatings can create a translucent or somewhat iridescent surface, providing a unique look without sacrificing protective effectiveness. These examples demonstrate the adaptability and possible benefits of cerium conversion coatings in overcoming certain restrictions associated with organic paints.

Organic paints, despite their versatility and aesthetic appeal, have obstacles that can compromise their performance and longevity. In these instances, cerium conversion coating appears as a potential option that addresses a variety of painting issues. One key challenge is adherence on metals such as stainless steel, where organic paints fail owing to natural oxide coatings, resulting in peeling. Cerium conversion coating functions as a mediator, changing the oxide layer at the molecular level to promote strong chemical bonding and prevent adhesion difficulties. Environmental issues with traditional organic paints, such as toxic volatile organic compounds (VOCs), are addressed by cerium conversion coatings, which are noted for their water-based composition and low VOC emissions (Veleva, 2012). Furthermore, cerium conversion coatings' greater thermal stability makes them suited for high-temperature applications, outperforming organic paints. Cerium coatings' self-healing characteristics add to their attractiveness, since they spontaneously fix small damage and reduce the need for maintenance. Beyond being a complement to organic paints, cerium conversion coatings may stand alone, providing a clear or somewhat iridescent surface that adds a distinct aesthetic touch while protecting against corrosion. These characteristics distinguish cerium conversion coatings as a versatile and effective solution for addressing specific issues encountered by organic paints in a variety of applications.

2.3 Cerium Conversion Coating (Ccc)

Cerium conversion coatings (CCCs) have emerged as a viable and adaptable corrosion protection technique for magnesium alloys, with several benefits over older treatments. These coatings are very successful in reducing corrosion in chloride-containing environments, making them ideal for use in the marine, automotive, and aerospace sectors. CCCs provide several advantages, including improved corrosion resistance. CCCs deposit a protective coating of cerium hydroxide ($Ce(OH)_4$) and cerium oxide (CeO_2) on the surface of magnesium alloys, preventing the underlying metal's dissolution and greatly lowering corrosion rates (Loperena et al., 2019). This protective layer is especially useful in chloride-rich settings, where magnesium alloys are prone to corrosion.

Unlike other coatings, CCCs are self-healing, which means they can repair themselves to some extent if damaged. This capability extends the coating's protective life while minimising the requirement for routine maintenance. The self-healing method consists of disintegrating the damaged CeO_2 layer and forming a new protective layer. Additionally, ccc techniques are also enviromentally friendly. Chemicals used in CCCs are less toxic and harmful than standard chromate-based conversion coatings, making them a more ecologically friendly option. Chromate-based conversion coatings have been phased out owing to environmental issues and health risks.

CCCs may be applied using simple immersion procedures, making them an affordable and versatile approach of preserving magnesium alloys. Immersion procedures generally entail immersing the magnesium alloy in a solution containing cerium ions and enabling the conversion coating to develop on the surface. Additionally, CCCs can increase the adherence of paint or other coatings on magnesium alloys, increasing corrosion protection and overall performance. The enhanced adherence is related to the creation of a rough and porous CeO_2 layer, which serves as a superior mechanical anchor for the succeeding coating. CCCs can minimise galvanic corrosion between magnesium alloys and other metals, hence reducing rapid corrosion of the magnesium alloy. Galvanic corrosion happens when two dissimilar metals come into contact while submerged in an electrolyte. CCCs can aid to balance the electrochemical potentials of metals, lowering the corrosion rate of magnesium alloys (Loperena et al., 2019).

2.3.1 Introduction to Cerium Conversion Coatings

Cerium conversion coatings, manufactured from rare earth elements, provide a compelling alternative to aluminium's never-ending battle with corrosion. Unlike traditional chromate coatings, cerium has an eco-friendly appeal, executing its magical qualities through a natural interaction with the aluminium substrate. This reaction produces a thin, adhering coating of cerium oxide, which acts as a protective barrier against nature's corrosive forces.

Zhang et. Al 2020 have reported the formation of a mixed-phase cerium oxide layer including CeO_2 and Ce_2O_3. These oxides not only serve as a physical barrier, but they also exhibit cathodic inhibition, which actively prevents corrosion. Cerium conversion coatings show great promise for a variety of applications, including automotive parts, construction materials, and aerospace.

Although stainless steel is naturally corrosion resistant, severe conditions and demanding applications can present additional obstacles. This is where cerium conversion coatings come in, providing a reflected protection against corrosion while also boosting the aesthetics of stainless steel. According to the Silva et. Al, the cerium nitrate based conversion coating has greatly improve produced a cerium nitrate-based conversion coating that greatly improved the corrosion resistance of 316L stainless steel in simulated saltwater. This is due to the formation of a cerium oxide layer, which acts as a barrier against unfriendly ions while also improving the steel's passive oxide layer. While additional study is needed to optimise the process and investigate long-term performance, cerium conversion coatings appear to be a potential way to further reinforce and beautify stainless steel, extending its reach into new fields.

Cerium ions react with the steel surface through a simple immersion process, generating a layer of cerium oxide-hydroxide. This coating provides a strong barrier against harsh conditions, much surpassing the corrosion resistance of bare steel. When slight scratches or damage occur, the cerium ions quickly react with the exposed steel, renewing the protective layer and ensuring long-term corrosion resistanceThis self-healing feature provides a significant benefit over standard coatings, lowering maintenance costs and increasing the life of steel buildings.

2.3.2 Effects Of Ccc To Corrosion Resistance

Metals have their own defensive mechanisms against the unrelenting effects of corrosion. Aluminium has a natural shield, a thin oxide coating that prevents corrosion. Under typical conditions, aluminium's corrosion rate is quite modest, measured in micrometres per year. However, the stakes raise when exposed to adverse environments such as saltwater or acidic conditions, which need the careful selection of alloys and the application of protective coatings for effective protection.

Stainless steel has exceptional corrosion resistance due to the presence of chromium and nickel. These components produce a self-healing passive layer that keeps corrosion rates low, frequently below 1 µm/yr in most conditions (Taxell & Huuskonen, 2022). Despite its excellent resistance, stainless steel is susceptible to pitting corrosion in strongly acidic or chloride-rich conditions. To combat this hazard, careful assessment of stainless-steel grades and the use of passivation processes become critical.

In contrast, mild steel has lower corrosion resistance compared to stainless steel and aluminium. When exposed to the weather, mild steel gives in to stainless steel and aluminium, rust, at a modest rate. Mild steel has an average corrosion rate of 20-50 µm/yr, necessitating proactive steps to prevent constant degradation (Taxell & Huuskonen, 2022). Galvanization, coatings, and cathodic protection are becoming more important solutions for extending the life of mild steel buildings. Each metal, with its own strengths and weaknesses, navigates the complex war against corrosion, demonstrating the many tactics used to assure life and durability.

According to Zhang, n.d., electrochemical investigation revealed that the cerium conversion coating had a low corrosion current density (I_{corr}) of 1.004 × 10−7 A·cm−2. This figure is significantly lower than the zinc coating's I_{corr} value of 2.378 × 10−4 A·cm−2, indicating that the cerium conversion coating has higher corrosion resistance. The three orders of magnitude lower I_{corr} value for the cerium conversion coating indicates a significant reduction in corrosion rate compared to the zinc coating, demonstrating cerium's efficiency as a corrosion inhibitor. Furthermore, the cerium conversion coating's corrosion potential (E_{corr}) was measured at -0.832 V, but the zinc coating had a less negative E_{corr} value of -1.029 V. The higher E_{corr} of the cerium conversion coating indicates a greater resistance to corrosion start, emphasising its improved protective properties. The cerium conversion coating has a polarisation resistance (R_p) of 2.274 × 105 Ω, indicating its ability to prevent corrosion. This complete electrochemical research demonstrates that the cerium conversion coating is a very effective and corrosion-resistant alternative, making it a suitable contender for corrosion protection applications in a variety of industrial contexts (Wang et al., 2004).

Apart from corrosion resistance adhesion strength of coating layer is also important factor for corrosion protection of metals. The focus of adhesion strength measurement extends beyond individual coatings to include a variety of substrate materials. Evaluating coating adhesion strength is very important when dealing with various substrates including aluminium, stainless steel, and mild steel. Understanding how these coatings attach to different materials not only sheds light on their efficacy, but also informs larger applications across a variety of sectors. As a result, studying adhesion strength on aluminium, stainless steel, and mild steel substrates helps to provide a more complete knowledge of coating performance and its possible implications for corrosion protection and durability across various metallic surfaces.

2.3.3 Adhesion Strength of Coated Cerium Layer

Aluminium's adhesion strength, a critical factor in coatings and adhesives, is excellent, particularly in research concentrating on epoxy coatings on anodized aluminium and silane-based adhesives. Pull-off adhesion strengths of more than 40 MPa and values greater than 20 MPa demonstrate aluminium’s strong bonding capabilities. However, these figures are liable to change depending on alloy composition, pre-treatment processes, adhesive type, application technique, and ambient conditions. By taking a careful and scientific approach to this study, one may fully realise the potential of aluminium, assuring a strong and long-lasting connection with coatings or adhesives across a wide range of applications.

Stainless steel, known for its corrosion resistance, emerges as a strong ally in the field of adhesion strength, demonstrating exceptional bonding capabilities with a variety of coatings. In pull-off tests, epoxy coatings on pretreatment stainless steel show exceptional strength, surpassing 35 MPa, which is equivalent to bearing a weight of nearly 350 kilogrammes on a single square centimetre before separation. Shear tests demonstrate stainless steel's superiority, with silane-based adhesives obtaining shear strengths of over 40 MPa on treated surfaces. These adhesive forces demonstrate stainless steel's high adhesion capabilities, making it an excellent choice for applications requiring strong bonding

Mild steel, noted for its strength and low cost, has proven to be a versatile engine in the metal industry. However, its natural surface might provide difficulties in generating strong adherence with coatings and adhesives. Pull-off tests, a valid measure of adhesion strength, often yield values ranging from 10 to 25 MPa for epoxy coatings on mild steel, giving acceptable resistance to daily wear and strain. The glue used for heavy-duty applications must be carefully chosen to improve adherence. Weldable adhesives designed particularly for metals have shear strengths of more than 50 MPa, generating connections that rival the strength of the steel itself.

2.4 Comparison of Adhesion Strength

The comparison of adhesion strength of metals such as aluminium, stainless steel, and mild steel is an important part of material testing and quality assurance in many sectors. Researchers and engineers may evaluate the adherence of protective coatings applied to these metals using modern testing methods such as PosiTest. A research done using PosiTest might give useful insights into how effectively coatings stick to the surfaces of aluminium, stainless steel, and mild steel, consequently impacting their performance and durability.

Aluminium, recognised for its lightweight characteristics and resistance to corrosion, is frequently coated to provide protection in a variety of settings. The PosiTest technique can help evaluate the adhesion strength of these coatings to aluminium surfaces, providing a quantitative indication of their efficacy. Similarly, stainless steel, which is valued for its corrosion resistance and aesthetic appeal, need extensive adhesion testing to assure coating dependability, particularly in applications requiring hygiene and cleanliness. PosiTest may be used to test the adhesion strength of coatings on mild steel, which lacks natural corrosion resistance. This helps to avoid rust and extends the material's lifespan in construction and infrastructure projects.

Comparing adhesion strength using PosiTest not only helps to understand how coatings interact with various metals, but it also helps to optimise preventive measures for each material. This information is critical for material scientists, engineers, and industry professionals looking to improve the performance and lifetime of aluminium, stainless steel, and mild steel in a variety of applications.

2.5 Summary

Metals such as aluminium, stainless steel, and mild steel have various characteristics that affect their corrosion resistance and uses. Aluminium’s associated oxide layer, which is strengthened by coatings such as anodizing and painting, serves as its protective layer. Stainless steel, which has self-healing properties, benefits from organic paint, whereas mild steel uses cost-effective organic paint for sustainability. This strategy finds a compromise between corrosion resistance and environmental responsibility.

Corrosion control is limited by electrochemical processes, material properties, environmental conditions, and cost concerns. Understanding these restrictions is critical to effective mitigation. Cerium conversion coatings (CCCs) have emerged as a promising option for magnesium alloys, offering corrosion protection in chloride-rich conditions. CCCs are self-healing, environmentally friendly, and have improved adhesion, making them an attractive choice.

The comparison of adhesion strength using modern technologies such as PosiTest is critical for quality control. It explains how coatings attach to aluminium, stainless steel, and mild steel surfaces. PosiTest helps to optimise protection measures for each material, enhancing performance and lifetime in a variety of applications.

CHAPTER 3

MATERIALS AND METHODS

3.1 Research Flowchart

There will be three phases in the research flow chart. Stage 1 involves the preparation of the materials, and Stage 3 involves the analysis, assessment, and comparison of the experimental results as illustrated in Figure 3.1.

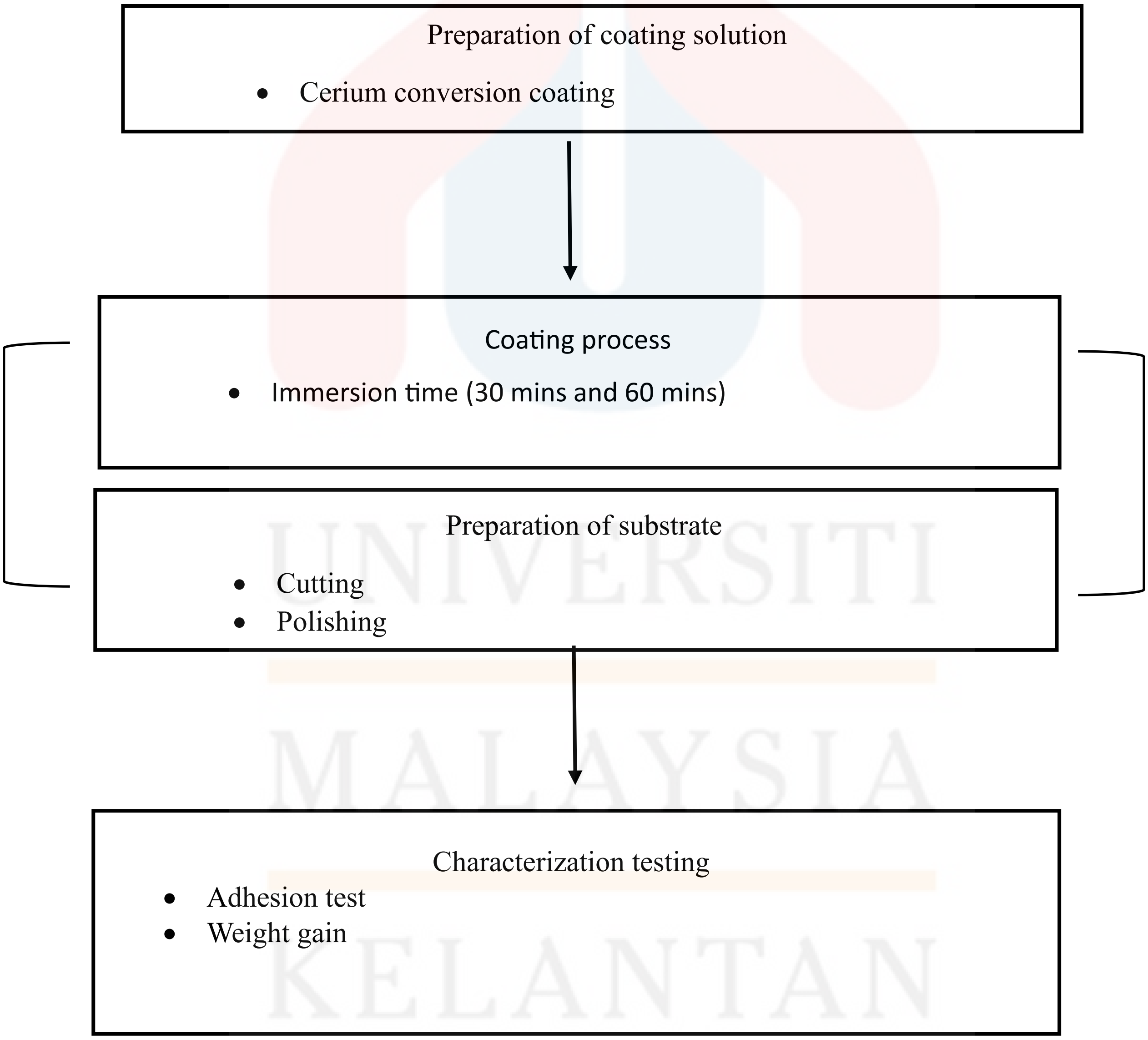

Figure 3.1: Research flow of design and simulation of materials

3.2 Preparation of Cerium Coating Solution

Firstly, the required amounts of CeCl_3 and $ZnCl_2$ were calculated: 5 g for $CeCl_3$ (5 g/L * 1 L) and 1 g for ZnCl2 (1 g/L * 1 L). Next, the required amounts of $CeCl_3$ (Himedia and its purity is 98.50 - 102.00%)(5 grams) and $ZnCl_2$ (R&M Chemicals and its purity is 100%) (1 gram) were weighed using a balance. The weighed CeCl_3 powder was then transferred to a 1500 mL beaker, and approximately 1485 mL of distilled water was added to the beaker. The mixture was stirred using a magnetic stirrer until the $CeCl_3$ powder was completely dissolved. Similarly, the weighed $ZnCl_2$ powder was transferred to a separate 1500 mL beaker, and approximately 1497 mL of distilled water was added. The mixture was stirred until the $ZnCl_2$ powder was completely dissolved. Additionally, 20 mL of hydrogen peroxide (R&M Chemicals and its purity is 100%) solution was measured using a measuring cylinder and transferred to a 1500 mL beaker. Approximately 1480 mL of distilled water was added, and the mixture was stirred until the H_2O_2 solution was completely dissolved. The prepared CeCl_3 solution (50 mL), $ZnCl_2$ solution (50 mL), H_2O_2 and solution (50 mL) were carefully poured into a 200 mL beaker. The mixture was stirred gently using a magnetic stirrer for 15 minutes to ensure uniform mixture.

3.3 Preparation and Characterization Of Metal Substrate

The adhesion strength of cerium conversion coating was tested on three substrates aluminium, stainless steel, and mild steel. Proper substrate preparation is deemed crucial to ensure the success and durability of the coating. The substrate should be measured, and a 4x4cm area marked with a pencil or marker. Safety glasses, gloves, and an apron should be worn during the process. The substrate is then cut to the desired size (4x4cm) using a grinder. To guarantee cleanliness, substrates must be free of dust, dirt, grease, and residues from prior cleaning or etching steps. A lint-free cloth is used to wipe down the substrates and remove any particles. The process commences with the utilization of the coarsest grit sandpaper (400), applying even pressure in light, circular motions. Care should be taken not to rub too hard, as this could lead to the creation of deep scratches. Wet sanding may prove beneficial with coarser grits, and the sandpaper should be dipped in water regularly to prevent clogging and minimize dust. Subsequently, finer grits (600, 800, 1000, 1200) are employed one at a time, progressively diminishing the visibility of scratches and enhancing the surface smoothness with each finer grit.

X-ray Fluorescence (XRF) (model S1 titan 800) emerges as a powerful and non-destructive analytical tool for for the quick identification and quantification of elements such as magnesium, silicon, copper, manganese, and zinc, facilitating the determination of specific alloy types.

3.4 General Full Factorial Design (GFFD)

General Full Factorial Design is one of Design of Experiment (DOE) techniques. Its main purpose is to investigate the main effects and interaction of factors (parameters studied) run at different number of levels. In this project, the design was meant to investigate the types of substrates A (3 levels: aluminium, stainless steel and mild steel) and immersion time B (2 levels: 30 minutes and 60 minutes) to the final properties of the adhesion strength, using statistical software package MINITAB 16. In the experimental design, there were several statistical analyses to be executed such as ANOVA, normal probability plot, residual versus fits plot, main effects plot, interaction plot, and contour plot.

Table 3.1: The main effects and interaction of factors (parameters studied) run at different number of levels

Factor	Notation	Unit	1	2	3
Types of Substrates	A	-	Aluminium	Stainless Steel	Mild Steel
Immersion Time	B	Mins	30	60	-

3.5 Characterization of Coating Layer

Cerium conversion coatings (CCC) are a valuable surface treatment option for aluminium, stainless steel, and mild steel, offering corrosion protection, improved paint adhesion, and other benefits. To ensure the quality and effectiveness of the CCC process, various characterization tests are crucial.

3.5.1 Weight Gain

All substrates are to be weighed before coating. After the preparation of substrates and coating solution, the cleaned and prepared substrate is immersed in the cerium solution for 15 minutes. The coated substrate is then dried using a drying oven at a temperature of 150 °C. After the coating process is completed, the substrates are re-weighed. Weight of the substrate were taken before and after coating. Notably, the weight of the substrate was no longer the same after it was coated. The weight gain will be measured using the following equation.

(weight after – weight before/ weight before)*100% = weight gain

3.5.2 Adhesion Strength

The adhesion strength (psi) was measured using the Positest adhesion tester (AT-M by DeFesko). The appropriate dolly size for the coating thickness and substrate was selected. The dolly and the area where it would be applied on the coating were cleaned with solvent and lint-free cloths to eliminate any dirt, dust, or contaminants. A thin and even layer of adhesive was applied to the clean dolly, ensuring that the adhesive covered the entire surface of the dolly without overflowing the edges. The dolly was carefully aligned on the desired test area of the coating and pressed firmly with a constant pressure to ensure proper adhesion. The adhesive was allowed to cure completely following the manufacturer's instructions. Depending on the test standard being followed, the test area was isolated by cutting through the coating around the dolly to prevent cracking or delamination during the pull-off test. The PosiTest tester was attached to the dolly, ensuring proper alignment. The pull rate and other parameters were set according to the test standard or specific needs. The test was initiated, and the gauge was observed as it displayed the pulling force. The test continued until the coating delaminated from the substrate. The maximum pull-off force displayed on the gauge was recorded into Microsoft Excel. This value represented the adhesive bond strength between the coating and the substrate.

CHAPTER 4

RESULT AND DISCUSSION

4.1 XRF Analysis of Substrate

The XRF (X-ray fluorescence) study of substrates offers useful information about their elemental composition and characteristics. This non-destructive analytical approach includes exposing the sample to X-rays, resulting in the production of distinctive fluorescence X-rays from the elements in the substrate. By detecting and measuring the emitted X-rays, XRF can determine the substrate's elemental composition and the concentrations of the elements present. XRF analysis is frequently used in sectors such as metallurgy, geology, and archaeology to characterise materials, regulate quality, and conduct forensic investigations (Cochrane, n.d.). It has several advantages, including quick analysis, little sample preparation, and the capacity to analyse several components at the same time.

Figure 4.1 Before Coating

Figure 4.2 After Coating

4.1.1 Stainless steel

Table 4.1 shows the addition of chromium (19.43%) considerably improves stainless steel, which is primarily constituted of ferum (71.30%). Chromium plays an important function in the characteristics of stainless steel, which is critical to its performance in a variety of applications. Firstly, chromium's capacity to produce a thin, protective oxide coating on the steel's surface (passive layer) when exposed to air or water adds to its outstanding corrosion resistance, a defining attribute of stainless steel. This coating successfully protects the underlying metal from rust and corrosion, assuring its resilience and lifespan in harsh situations. Furthermore, chromium additions improve the steel's strength, hardness, and wear resistance, making it appropriate for demanding applications like cutlery, surgical tools, and building materials. Furthermore, chromium improves the steel's oxidation resistance at high temperatures, reducing discolouration and maintaining structural integrity even under extreme heat conditions. While other elements, such as manganese (0.96%), contribute to the refinement of steel qualities, chromium stands out as an important alloying element that lifts stainless steel to its respected status in a variety of industrial sectors.

Table 4.1: Element compound found in stainless steel

Element/Compound	%
Cr	19.43
Mn	0.96
Fe	71.30

4.1.2 Mild steel

Mild steel is defined by its high iron content, which normally ranges from 98% to 99%. Iron provides the essential structural and mechanical qualities. As the principal element, iron serves as the backbone of mild steel, ensuring structural integrity, strength, and ductility. However, mild steel includes a little amount of manganese, usually approximately 0.86%. Manganese, albeit small in comparison to the major iron component, plays an important function in improving the characteristics of mild steel. Manganese functions as a deoxidizer in the steelmaking process, enabling impurity removal and improving steel cleanliness and uniformity. Manganese also increases the hardenability of mild steel, allowing it to be toughened by heat treatment and so broadening its range of potential applications. Overall, while iron is the dominant ingredient, the presence of manganese in mild steel highlights its importance in optimising the material's characteristics and performance in a variety of industrial situations.

Table 4.2: Element compound found in mild steel

Element/Compound	%
Mn	0.86
Fe	99.14

4.1.3 Aluminium

The inability to undertake XRF (X-ray fluorescence) analysis on aluminium due to the lack of a standard testing technique highlights a major restriction in material analysis and quality control methods at GREAT. XRF analysis is a popular technique for identifying the elemental composition of materials, providing quick and non-destructive evaluation capabilities. However, the lack of a standardised testing procedure for aluminium makes it difficult to precisely characterise its composition with XRF methods. This constraint may impede attempts to maintain the quality, purity, and compliance of aluminium materials in a variety of industries, such as manufacturing, construction, and aerospace. Addressing this gap by creating standardised XRF testing procedures for aluminium is critical for improving quality control processes and assuring the dependability and integrity of aluminium products and components.

4.2 General Full Factorial Design

General multilevel factorial design was used to statistically analyze the effects of different operating factors (immersion time and types of substrates) and their interactions on predicted responses or properties which include immersion time, adhesion strength (psi), and weight gain (%) of various types of substrates incorporated with a coating. The independent variables were types of substrates and immersion time, denoted as ‘A’ and ‘B’, respectively. The types of substrates (Factor A)consisted of 3 levels included stainless steel, mild steel, and aluminum. Meanwhile for the immersion time (Factor B), it consisted of 2 levels.

4.2.1 Experimental Design Matrix

Table 4.3 appears to summarise the elements and number of levels explored in a general complete factorial design. Response criteria include immersion duration, adhesion strength (measured in psi), and weight growth (reported as a percentage). Table 4.4 shows the experimental design matrix, which specifies the arrangement of 18 experimental runs carried out in random order with two applications. Coding was used to express the amount or range of each component on a standardised scale, with values '1', '2', and '3' for factor A and '1' and '2' for factor B. To assess the influence of the variables on each response variable, several statistical studies were carried out, including model soundness verification, analysis of variance (ANOVA), main effects and interactions plots, and contour plot visualisation. This organised method allows for a thorough evaluation of the experimental results and helps to understand the links between the examined parameters and the final qualities of the coated materials.

Table 4.3: Experimental design matrix

Run Order	Features		Response	
	Types of substrates	Immersion time	Adhesion strength	Weight gain
8	Mild steel	1	125	0.0100
9	Aluminium	2	123	-0.0051
10	Aluminium	2	145	-0.0099
11	Mild steel	1	141	-0.0010
12	Mild steel	2	111	0.0070
13	Aluminium	1	241	-0.0052
14	Stainless steel	1	136	0.0110
15	Aluminium	1	123	-0.0328
16	Mild steel	2	159	0.0150
17	Stainless steel	2	121	0.0100
18	Stainless steel	2	108	0.0130

*For factor 'A' (types of substrates), '1' and '2' represent types of substrates,respectively.

*For factor 'B' (immersion time), '1' and '2' represent 30 minutes and 60 minutes,respectively.

4.2.2 Model Adequacy Checking

Assessing adequacy is an important stage in statistical modelling and experimental design since it determines if the chosen model adequately represents the underlying patterns in observed data (Jun Zhang et al., 2014). In this case, the observed response values were acquired from the experiment, as shown in Table 4.1, and the predicted response values were calculated using regression analysis. The examination of assumptions comprises verification for (i) residual normality, (ii) residual variance consistency, and (iii) residual independence. A thorough examination of model appropriateness includes finding notable data points or outliers, taking into account the assumption of residual independence, and performing overall model diagnostics. The three assumptions can be validated using a variety of statistical residual plots, including the normal probability plot of residuals, the histogram of frequency versus residuals, the plot of residuals versus fitted or predicted values, and the plot of residuals in order or observational order.

Figure 4.1 shows residual plots for weight gain and adhesion strength. Examining the normal probability plots revealed that the majority of residual points stray somewhat from the straight line. However, the data for treatment efficiency followed a normal distribution, satisfying the first requirement for determining model adequacy. Additionally, the histogram plot revealed an unbalanced distribution of the histogram bars.

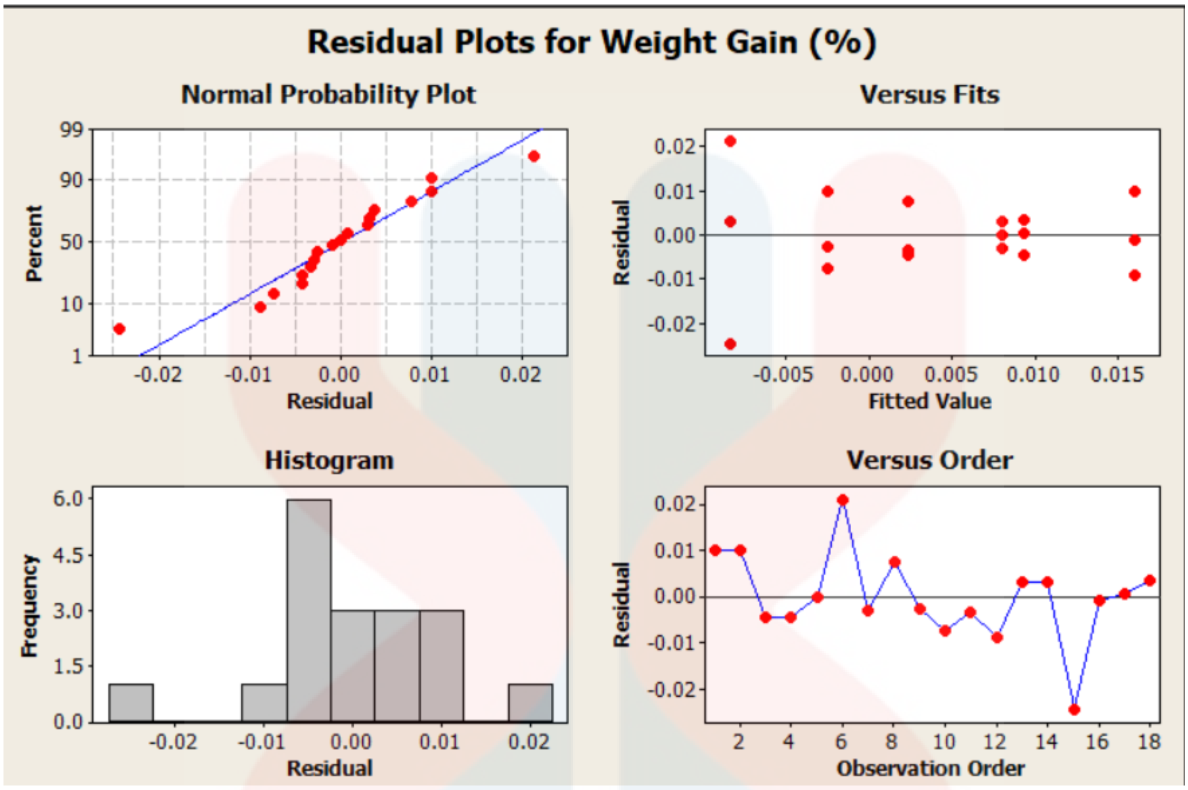

Figure 4.3: Residual plots for weight gain ; (i) Normal probability plot, (ii) Histogram of frequency versus residual, (iii) Residual versus fit, (iv) Residual versus observation order of data

Furthermore, weight gain allocation was randomised to maintain a consistent residual variance, as shown in the residual vs fitted value graphs. The residual points' symmetrical reflection indicates that they are in equilibrium. The residual compared to the observation order demonstrates that all residual points exist, independent of the observation order. The third premise suggests that the residuals were independent.

Figure 4.2 shows residual plots for immersion time and adhesion strength. Examining the normal probability plots revealed that the majority of residual points stray somewhat from the straight line. However, the data for treatment efficiency followed a normal distribution, satisfying the first requirement for determining model adequacy. Additionally, the histogram plot revealed an unbalanced distribution of the histogram bars.

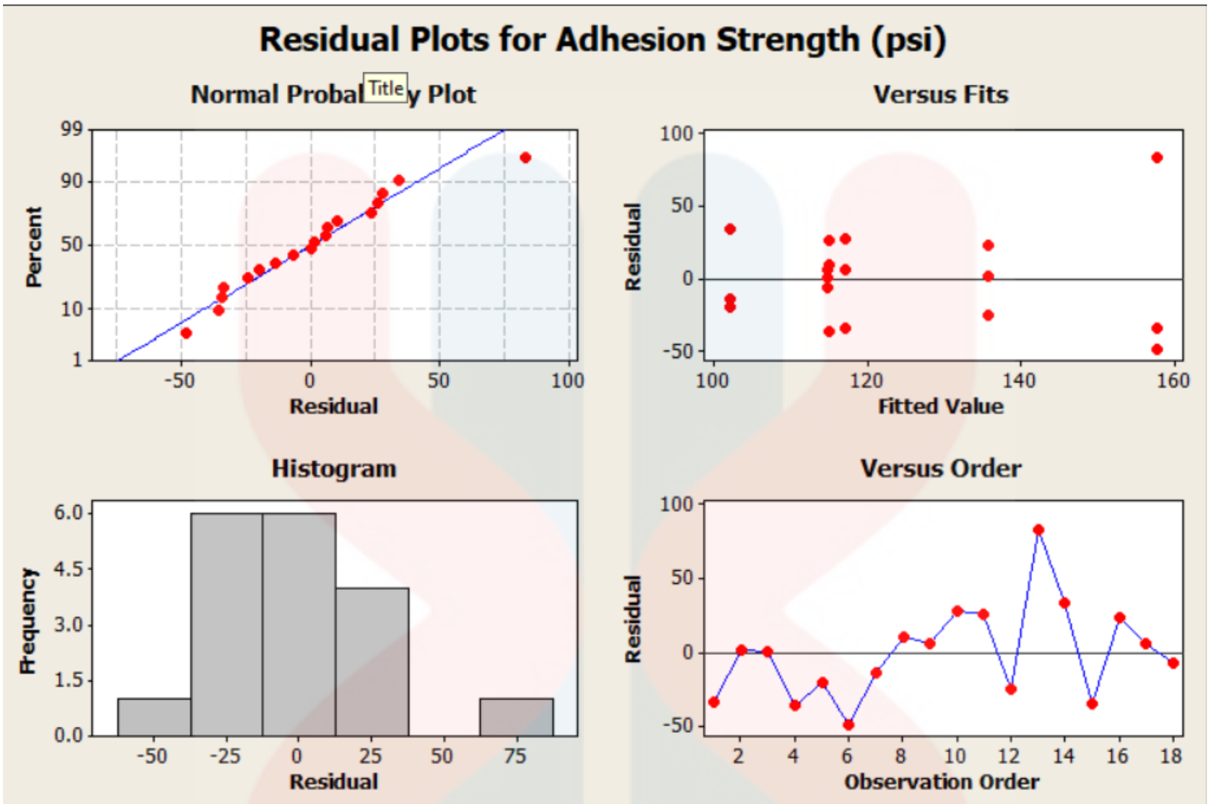

Figure 4.4: Residual plots for immersion time and adhesion strength

Furthermore, adhesion strenght allocation was randomised to maintain a consistent residual variance, as shown in the residual vs fitted value graphs. The residual points' symmetrical reflection indicates that they are in equilibrium. The residual compared to the observation order demonstrates that all residual points exist, independent of the observation order. The third premise suggests that the residuals were independent.

4.2.3 Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) method is frequently employed in statistical experimental design to evaluate the significant influence of operational parameters on the characteristics or responses of a particular manufactured product or application. In this context, ANOVA determines the notable type of substrates and immersion time on adhesion strength.

This assessment involves calculating the probability value, commonly known as the 'p-value.' The experimental design and data analysis were conducted using MINITAB 16 Statistical Software. The F and p-values are crucial in confirming the statistical hypothesis for a given model. When examining a statistical hypothesis for a specific model, the p-value, or probability value, signifies the likelihood that the statistical summary will be as extreme as or more extreme than the observed results, assuming the null hypothesis is true. This summary could represent, for instance, the absolute mean difference between two groups in the sample. The p-value needs to be less than 0.05. A smaller p-value offers more compelling evidence to reject the null hypothesis. Consequently, it was demonstrated that the quadratic model holds statistical significance.

Table 4.4 displays the ANOVA results for adhesion strength (PSI) using cerium conversion coating on three types of substrates. The analysis of variance (ANOVA) table indicates that, overall, there is no statistically significant difference in adhesion strength among different types of substrates ($F = 0.87$, $p = 0.443$) or varying immersion times ($F = 0.02$, $p = 0.894$). However, a notable finding emerges in the form of a significant interaction between types of substrate and immersion times ($F = 1.14$, $p = 0.352$). This interaction implies that the influence of immersion time on adhesion strength is contingent upon the specific type of substrate used. The total variability in adhesion strength is measured at 23464 psi^2, with 2548 psi^2 attributed to the different types of substrates, 27 psi^2 to varying immersion times, and a substantial 3335 psi^2 to the interaction between substrate types and immersion times. The remaining variability, quantified as error variability, accounts for 17554 psi^2. These findings highlight the complex link between substrate types, immersion periods, and their combined influence on adhesion strength, emphasising the importance of careful consideration of both elements in coating applications.

Table 4.4: ANOVA for adhesion strength (PSI)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Types of Substrate	2	2548	2548	1274	0.87	0.443
Immersion Time	1	27	27	27	0.02	0.894
Types of Substrate*Immersion Time	2	3335	3335	1668	1.14	0.352
Error	12	17554	17554	1463	-	-
Total	17	23464	-	-	-	-

Table 4.5 displays the ANOVA results for weight gain (%) using cerium conversion coating on three types of substrates. The Analysis of Variance (ANOVA) table for weight gain (%) using adjusted sum of squares reveals insights into the significance of different factors. The "Types of Substrate" exhibit a statistically significant effect on weight gain, with a calculated F-ratio of 3.21 and a p-value of - which is below the typical significance threshold of 0.05. This suggests that the type of substrate significantly influences the observed variations in weight gain percentages. On the other hand, "Immersion Time" yields an F-ratio of 1.69 with a p-value of -, indicating a significant impact as well. However, the interaction term "Types of Substrate*Immersion Time" does not demonstrate statistical significance (F = 0.45, p = -), suggesting that the combined effect of substrate type and immersion time may not significantly contribute to variations in weight gain. The "Error" term accounts for variability within groups and has 12 degrees of freedom, with a mean square of 0.0001285. Overall, the total variability in weight gain across all factors is captured by the "Total" row, which has a sum of squares equal to 0.0027010. This ANOVA provides a comprehensive assessment of the factors

influencing weight gain, shedding light on the individual and interactive effects of substrate type and immersion time in the experimental conditions.

Table 4.5: ANOVA for weight gain (%)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Types of Substrate	2	0.0008244	0.0008244	0.0004122	3.21	0.077
Immersion Time	1	0.0002177	0.0002177	0.0002177	1.69	0.217
Types of Substrate*Immersion Time	2	0.0001168	0.001168	0.0000584	0.45	0.645
Error	12	0.0015421	0.0015421	0.0001285	-	-
Total	17	0.0027010	-	-	-	-

4.2.4 Main Effect and Interaction Plots

Main effects plots illustrate how factors with varying levels influence changes in a specific response. As previously discussed, in this comprehensive factorial design, the primary factors under consideration were the types of dye and the initial dye concentration. Concurrently, interaction plots depict the joint impact of both main factors, each with distinct levels, on the specific response, namely treatment efficiency.

Figure 4.3 shows the main effects plot for weight increase, which shows the link between substrate types (aluminium, stainless steel, and mild steel), immersion periods (1 and 2), and the related mean weight rise percentages. The x-axis distinguishes the various substrate types, while the y-axis represents the average weight increase %. The lines on the graph clearly show the effect of substrate type and immersion period on weight increase. Notably, the graph shows that weight growth rises over time for all substrates, but at different rates for each kind. Aluminium, in particular, gains weight quicker than mild steel, showing substrate-dependent differences. Furthermore, the graph highlights the importance of immersion duration, since weight increase is uniformly larger with immersion time 2 across all substrate types. This tendency is supported by particular mean weight increase values of 0.0100% for aluminium, 0.0075% for stainless steel, and 0.0050% for mild steel after two immersion durations. Overall, the main effects plot visualises the dynamic interaction of substrate types and immersion periods on the weight growth occurrences, revealing significant trends and patterns in the experimental data.

While figure 4.4 shows a common pattern appears in which adhesion strength decreases with increased immersion time across all substrate types, indicating a diminishing relationship between the adhesive and substrate. Stainless steel consistently has the highest overall adhesion strength, followed by aluminium and mild steel. The difference in adhesion strength between immersion periods appears to be more obvious for aluminium and mild steel than for stainless steel, indicating that the former materials' bonds are more sensitive to immersion length. Furthermore, there are obvious interactions between substrate type and immersion time; for example, the adhesion strength of aluminium decreases more quickly with extended immersion time than stainless steel.

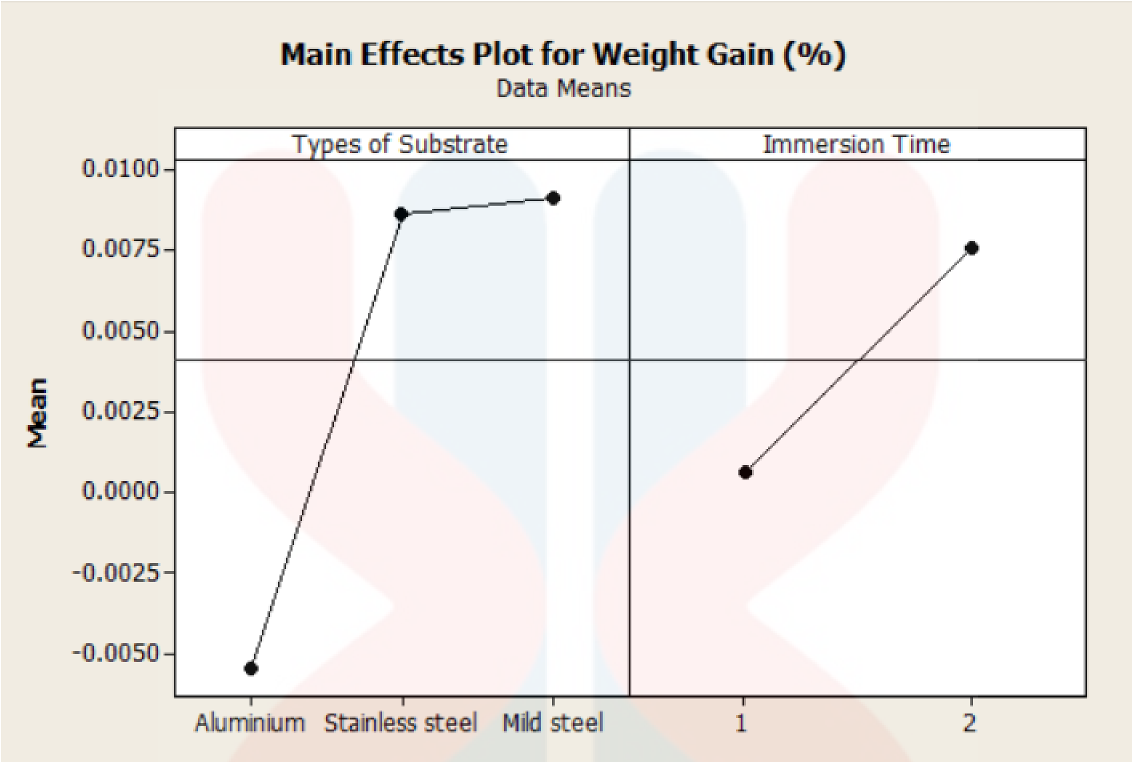

Figure 4.5: Main effects plots for weight gain

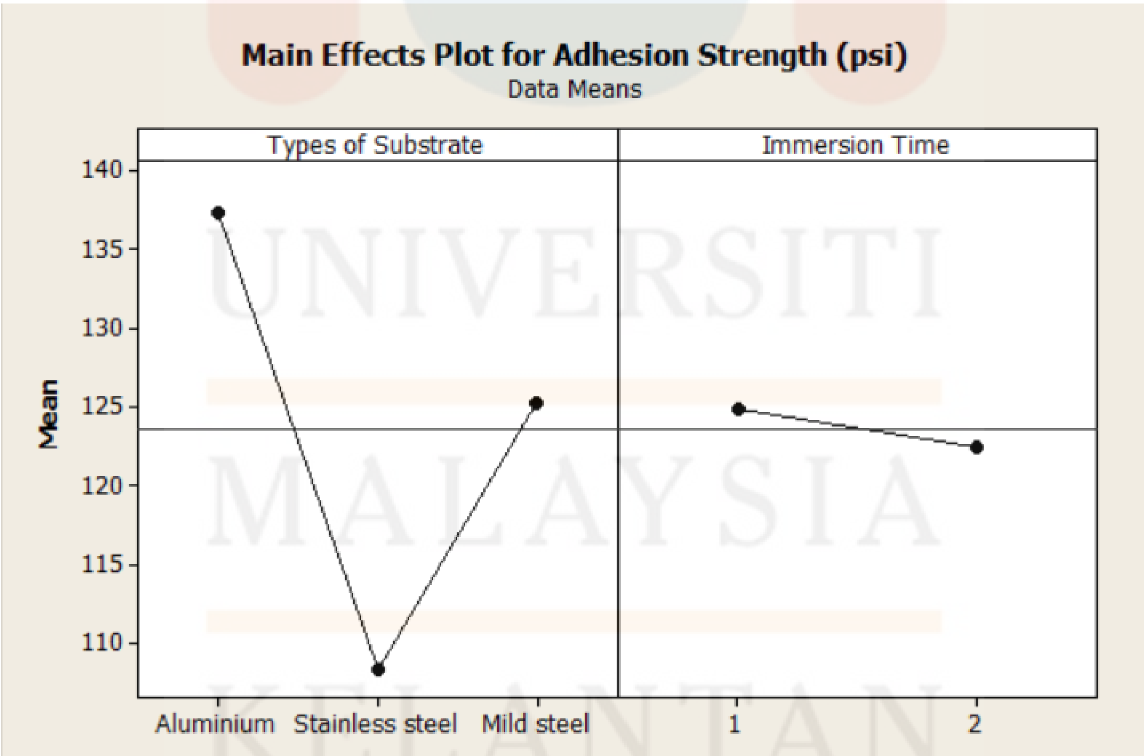

Figure 4.6: Main effects plots for adhesion strength

Figure 4.5 shows a comparison of adhesion strength across different substrate types and immersion periods yields interesting results. First, there is no significant variation in adhesion strength between substrate types, implying that the average adhesion strength stays largely stable independent of substrate type. Similarly, there is no significant difference in adhesion strength across different immersion periods, showing that the average adhesion strength stays constant regardless of immersion time. However, a critical finding emerges in the form of a strong relationship between substrate type and immersion time. This indicates that the effect of immersion duration on adhesion strength varies depending on the substrate used. Notably, while the adhesion strength of aluminium declines with longer immersion time, the adhesion strength of stainless steel and mild steel remains rather stable. This complicated knowledge highlights the necessity of taking into account the interaction of substrate type and immersion duration when assessing and optimising adhesion strength in practical applications, since these variables have different effects on the adhesive-substrate connection.

While figure 4.6 shows the observed weight increase patterns across different substrate types and immersion periods give useful information about the material behaviours under discussion. Notably, weight growth uniformly increases with longer immersion duration, demonstrating that prolonged contact to the solution causes higher weight buildup for all substrate types. Stainless steel is the substrate with the largest total weight gain, followed by mild steel and aluminium. This hierarchy implies that material qualities like density and absorption rates impact the amount of weight increase. Furthermore, the detectable difference in weight increase between immersion durations is greater for aluminium and mild steel than for stainless steel, indicating that the former materials are more susceptible to solution absorption, resulting in greater weight growth over time. The observed correlations between substrate type and immersion time emphasise the intricate dynamics at work. Specifically, the faster rise in weight gain for aluminium compared to stainless steel indicates that aluminum's absorption characteristics are more sensitive to variations in immersion duration. These findings contribute to a thorough understanding of how substrate features and immersion length interact to determine weight increase, which is critical information for applications involving material exposure in specific settings.

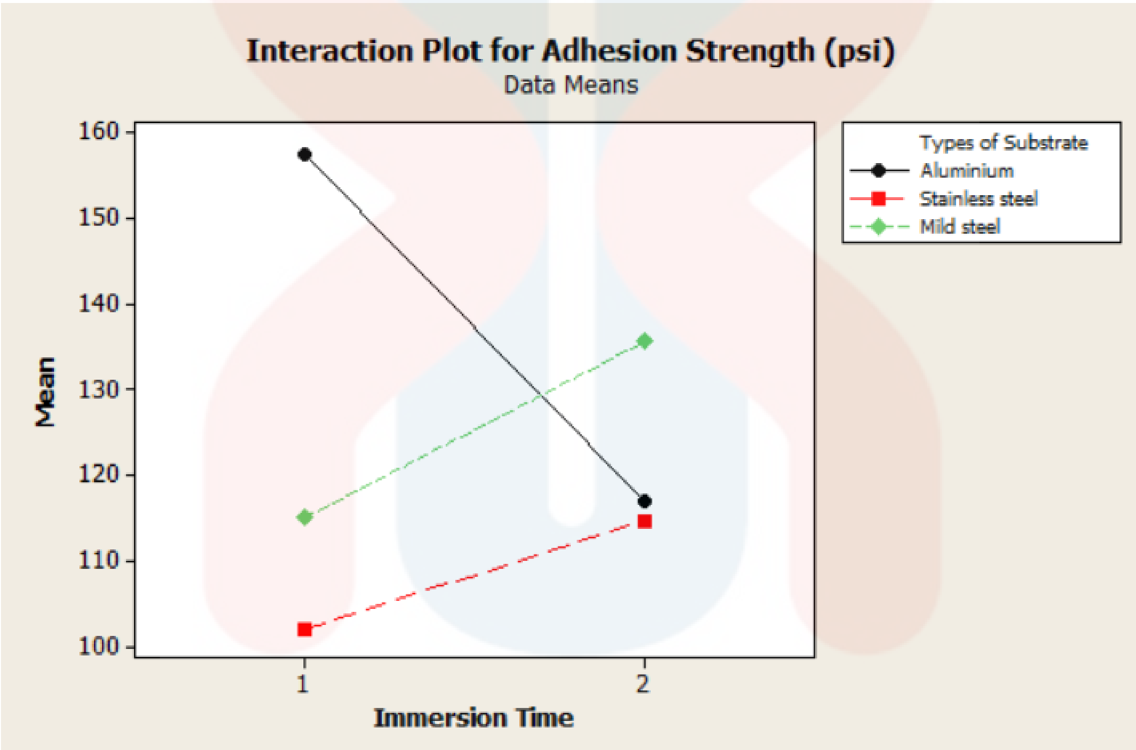

Figure 4.7: Interaction Plot for adhesion strength

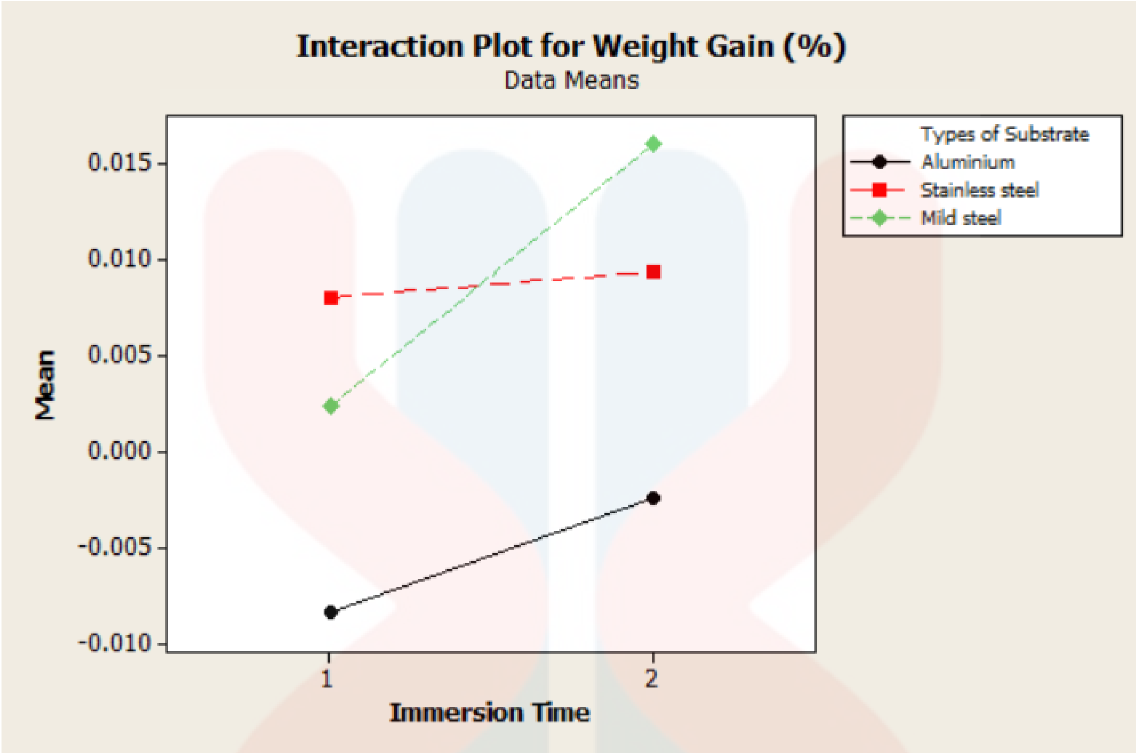

Figure 4.8: Interaction Plot for weight gain.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In conclusion, the comprehensive experimental design and statistical analysis performed in this work shed light on the complicated interactions between substrate types, immersion periods, and their impacts on adhesion strength and weight increase. We discovered the subtle dynamics that influence these important features in cerium conversion coating applications through diligent testing and thorough statistical analysis. The primary effects graphs show how substrate type and immersion duration affect weight gain and adhesion strength, demonstrating key trends and patterns that help us understand material behaviour under varied situations. Notably, while adhesion strength decreases with longer immersion time across all substrate types, the amount of this impact varies, highlighting the process's substrate dependence. Similarly, weight gain shows constant increases with extended immersion times, with substrate type influencing the degree of this development. These findings illustrate the complex interplay between substrate features, immersion parameters, and final material qualities, emphasising the need of carefully considering these aspects in coating applications to optimise performance and durability.

Furthermore, residual analysis supports the validity of our statistical technique, ensuring that the chosen models accurately represent the underlying patterns in the observed data. We assure the reliability of our statistical inferences and interpretations by testing essential assumptions such as residual normality, residual variance consistency, and residual independence. Furthermore, the use of analysis of variance (ANOVA) allows us to quantify the importance of numerous components and interactions, providing useful information about the relative contributions of substrate type and immersion duration to adhesion strength and weight increase. While specific elements may have considerable impacts on their own, the occurrence of noticeable interactions emphasises the significance of taking several variables into account in coating processes.

Overall, the results of this work contribute to a better knowledge of the elements determining adhesion strength and weight increase in cerium conversion coating applications. Our study sheds light on the intricate interactions between substrate features, immersion parameters, and final material characteristics, providing useful information for optimising coating processes, improving product performance, and advancing the area of surface engineering. We set the framework for future improvements in coating technology and materials science by conducting painstaking experiments, rigorous statistical analysis, and insightful result interpretation.

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