CP- 301: Development Engineering Project
Stealth Coatings for Radar Absorption

End-Semester Report

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Submitted on: 8th May, 2025

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CANDIDATE'S DECLARATION

We hereby certify that the work which is presented in the report, entitled "**Stealth Coatings for Radar Absorption**" in part fulfilment of the requirement for the award of the Degree of Bachelor of Technology and submitted in the Department of Mechanical Engineering of Indian Institute of Technology Ropar is an authentic record of our own work carried out during a period from January, 2025 to May 2025 under the supervision of Prof. Dr. Harpreet Singh.

The matter presented in the report has not been submitted by us for the award of any other degree of this or any other University/Institute.

(CHAHAT, MILI PRAJAPATI, PALAKPREET KAUR)

Signature of the Candidates

This to certify that the above statement made by the candidate is correct to the best of my knowledge

Date: May 8, 2025

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Acknowledgements

We would like to express our thanks and gratitude to Professor Dr. Harpreet Singh for his continued support and guidance in helping us complete our project by exploring the different routes and methods to analyse the problem. His immense knowledge and plentiful experience has encouraged us in all the time of our project work. Without his guidance, we would not have been able to come so far in this project successfully. We really appreciate his sincere and valuable guidance.

Additionally, we express our sincere appreciation to Saiful Sir and Ammey Ma'am. Their valuable insights, encouragement, and support have been indispensable in navigating the complexities of our project. Their contributions have greatly enriched our understanding and propelled us forward towards our goals.

We would also like to express our sincere gratitude to the workshop staff of our college for their constant support and assistance towards our project. Their expertise, technical knowledge and guidance have been invaluable to us. They provided us with the necessary equipment, material and technical support which were essential for carrying out this project. They also helped us during the designing and assembling of the final structure. The friendly and welcoming environment of the staff is highly appreciated. Their warm and welcoming nature made it easier for us to work in the workshop, and we felt comfortable seeking help from them whenever needed.

We want to say our sincere thanks to Indian Institute of Technology, Ropar for giving us an opportunity to explore the outside world and being a part of expanding our creative minds in developing an idea to solve an existing and crucial problem.
We would also like to thank our friends, colleagues and others for their support and assistance whenever we needed it. Our appreciation also goes to our families and friends for their encouragement and support all throughout our project.

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1.Abstract

Stealth technology is crucial for reducing military assets' radar cross-section (RCS) by utilizing radar-absorbing materials and optimized geometric designs. This study begins with a comprehensive literature review to evaluate suitable materials for stealth coatings, focusing on their radar absorption efficiency, durability, and cost-effectiveness. Based on these findings, we are exploring thermal spray techniques for coating applications, as they provide uniform, durable, and efficient layers of radar-absorbing materials.

We planned to develop and compare stealth coatings using two different thermal spray methods based on material compatibility:

- Ceramic-based coatings (SiC/Al_2O_3 and ZrC/Al_2O_3) using Plasma Spray, as this technique effectively applies ceramic materials.
- Metal Matrix Composite (MMC) coatings (SiC/Al_2O_3/metal and SiC/Al_2O_3/metal) using Cold Spray, since cold spray is more suitable for metal-based applications without compromising material integrity.

These coatings will be evaluated and compared regarding *stealth efficiency, durability, and structural integrity.* The study aims to determine the most effective combination of materials and application techniques for optimizing stealth coatings. The results will contribute to advancements in stealth technology, providing valuable insights for both military and civilian applications.

2.Introduction

Stealth technology encompasses a range of design and material strategies aimed at reducing an object's visibility to radar, infrared (IR), sonar, and other detection systems. It is primarily utilized in military contexts to enable aircraft, ships, and vehicles to evade detection, and is achieved through optimized geometries, electromagnetic (EM) wave-absorbing coatings, and thermal signature suppression. A notable example is the Northrop Grumman B-2 Spirit, which uses radar-absorbing materials (RAMs) and an angular shape for reduced radar cross-section.

Radar systems typically operate in the microwave region (300 MHz to 300 GHz), with stealth coatings targeting absorption or deflection within specific bands such as the L-band (1–2 GHz), S-band (2–4 GHz), X-band (8–12 GHz), and higher Ku, K, and Ka bands (12–40 GHz). RAMs reduce radar reflection through mechanisms like impedance matching, dielectric and magnetic loss, and multiple internal reflections. Conventional RAMs include ferrite-based (magnetic loss), carbon-based (high conductivity, but oxidation-prone), and ceramic-based (thermally stable, dielectric loss) materials.

Ceramics like Zirconium carbide (ZrC) are of particular interest due to their high melting point (~2450°C), and mechanical resilience. As a P-type semiconductor, SiC shows promising microwave absorption, especially when integrated with magnetic materials like FeB to introduce magnetic loss. Al_2O_3 is frequently used as a stable ceramic matrix in these applications.
This study explores advanced stealth coatings using thermal spray techniques, including plasma and cold spray methods. Two core systems will be examined: SiC/Al_2O_3 and ZrC/Al_2O_3, and their metal-enhanced versions (SiC/Al_2O_3/metal, ZrC/Al_2O_3/metal) to improve conductivity and mechanical bonding—especially suitable for cold spray deposition. The coatings will be assessed for radar absorption across multiple bands, thermal and oxidation resistance, durability under mechanical stress, and IR signature suppression.

Ultimately, this work aims to develop next-generation stealth coatings with improved performance for both military (UAVs, aircraft, naval platforms) and civilian (EM shielding, medical imaging) applications.

3.Problem Statement

3.1 Limitations of Traditional RAMs:

Traditional radar-absorbing materials (RAMs), such as ferrite-based or carbon-based composites, have long been used in stealth technology. However, they face several challenges, particularly when applied to the aircraft fuselage and wings. These materials often exhibit poor thermal stability and mechanical durability, especially under the high-speed, high-altitude, and high-temperature conditions typical in aerospace environments. Their absorption performance may also degrade over time due to environmental exposure, mechanical vibrations, or thermal cycling, making them less reliable for long-term stealth applications.

3.2 Need for Advanced Ceramic-Based Coatings:

To overcome the shortcomings of conventional RAMs, there is a growing need to explore advanced materials like ceramic-based coatings, specifically SiC/Al_2O_3 and ZrC/Al_2O_3 systems. These ceramics offer excellent thermal stability, chemical inertness, and mechanical hardness, making them well-suited for extreme aerospace conditions. When applied through thermal spray techniques such as plasma spraying, these coatings can potentially deliver better radar absorption across critical frequency bands (e.g., S-band and X-band) while maintaining structural integrity under thermal and aerodynamic stress.

3.3 Potential of Metal Matrix Composite (MMC) Coatings:

To further enhance performance, metal matrix composite (MMC) coatings such as SiC/Al_2O_3/metal and ZrC/Al_2O_3/metal are being considered. These coatings combine the high-temperature resistance of ceramics with the electrical conductivity and toughness of metals, creating a synergistic effect for radar wave attenuation. The cold spray technique is particularly advantageous for MMCs, as it allows deposition at lower temperatures, preserving phase purity and avoiding oxidation. Moreover, the plastic deformation of metal particles during impact ensures strong bonding with the substrate and among the composite phases, improving adhesion and mechanical strength.

4. Literature Review

After reviewing multiple research papers and studying various traditional materials used in stealth coatings, we analysed the properties of different materials to determine their effectiveness in radar absorption. Through this extensive study, we identified that ZrC/Al_2O_3 exhibits promising stealth properties due to its excellent radar wave absorption capabilities. Various factors such as *dielectric properties, thermal stability, adhesion strength, and reflection loss* were considered to finalize the materials for further experimentation.

4.1 The Process Flow

4.1.1 Preparation of Pallets

1. Fabricating pallets of different compositions of selected materials to assess their anti-radar absorption properties.
2. Ensuring uniformity in material distribution for accurate evaluation.

4.1.2 In-depth Characterization of Pallets

1. Conducting a detailed analysis of the fabricated pallets to determine their physical, chemical, and radar-absorbing properties.
2. Performing X-ray Diffraction (XRD) to analyze the crystalline structure of the materials.
3. Conducting Scanning Electron Microscopy (SEM) to study the microstructure and surface morphology.
4. Identifying the optimized pallet composition with the best stealth performance.

4.1.3 Deposition of Optimized Coating

1. Applying the optimized material as a coating on aircraft components using suitable thermal spray techniques:
2. Plasma Spray for ceramic-based coatings (SiC/Al_2O_3, ZrC/Al_2O_3).
3. Cold Spray for metal matrix composite coatings (SiC/Al_2O_3/metal, ZrC/Al_2O_3/metal).

4.1.4 In-depth Characterization of Coating

1. Analysing the performance of the coated surface, including reflection loss, adhesion strength, microstructure analysis, and stealth efficiency.
2. Comparing results to determine the most effective coating and deposition technique using X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM).
3. This study aims to contribute to the development of high-performance stealth coatings, enhancing the radar invisibility of aircraft and advancing stealth technology.

4.2 Characteristics of Radar Absorbing Materials

4.2.1 Impedance Matching

1. Ensures minimal reflection of electromagnetic (EM) waves by matching the characteristic impedance of the coating with free space.
2. Calculated using the transmission line model, where reflection loss (RL) is minimized when Zin=Zo.
3. Influenced by parameters such as relative permittivity (ε*r*), permeability (μ*r*), coating thickness (d), and frequency (f).

As illustrated in **Figure 4.1**, when an EM wave encounters the surface of a radar absorbing material, the reflection can be minimized by matching the input impedance of the coating (Zin) to the impedance of free space (Zo). This condition, derived from the transmission line model, ensures optimal impedance matching and thus reduces the reflected wave intensity.

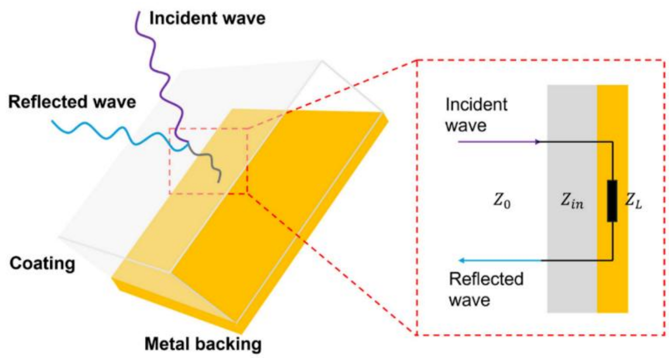

Figure 4.1: *Illustration of impedance matching in radar absorbing materials using the transmission line model. The reflection of incident electromagnetic waves is minimized when the input impedance (Zin) of the coating matches the free space impedance (Zo).*

[Reference:https://www.mdpi.com/2079-6412/14/5/607]

4.2.2 Magnetic Dissipation

1. Occurs due to magnetization and demagnetization processes in magnetic materials.
2. Determined by complex permeability ($\mu r=\mu'-j\mu''$), where μ'' represents energy loss.
3. **Hysteresis Loss**: Due to the movement of magnetic domains, independent of frequency.
4. **Eddy Current Loss**: Induced by alternating EM fields.
5. **Residual Loss**: Includes magnetic after effects and resonance losses.

4.2.3 Dielectric Dissipation:

1. EM energy is absorbed through conduction loss and polarization loss.
2. Described using complex permittivity ($\varepsilon r = \varepsilon' - j\varepsilon''$), where ε'' represents dielectric losses.
3. Types of dielectric losses
4. **Conductive Loss ($\varepsilon c''$)**: Proportional to electrical conductivity.
5. **Polarization Loss ($\varepsilon p''$)**: Includes interfacial polarization, dipolar polarization, and defect-induced polarization.

As shown in **Figure 4.2**, the effectiveness of dielectric loss mechanisms can be visualized in different materials, where variations in reflection coefficients highlight the role of conductive and polarization losses in minimizing EM wave reflection.

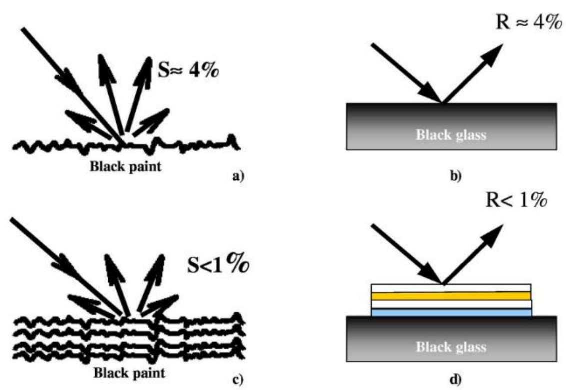

Figure 4.2: *Visual comparison of dielectric dissipation mechanisms in absorbing coatings. Higher absorption (lower reflectance) is achieved through combined conductive and polarization losses in black paint layers on glass substrates.* [Reference:https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10569/105690C/Design-and-manufacture-of-high-absorption-metal-dielectric-coatings-for/10.1117/12.2307944.full]

4.3 Multiple Reflections

1. Thin coatings allow EM waves to reflect multiple times within the material, leading to increased energy dissipation.
2. Effective only when the coating thickness is less than the skin depth (δ), beyond which absorption effects dominate.
3. The skin depth (δ) is inversely related to the conductivity (σ) and permeability (μ).
4. These characteristics are crucial in designing EM absorption coatings for applications such as stealth technology, electromagnetic shielding, and radar cross-section reduction.

Figure 4.3 illustrates the concept of multiple internal reflections within a thin radar absorbing material. These reflections enhance the EM wave path inside the material, increasing the opportunity for energy dissipation and absorption before reaching the substrate.

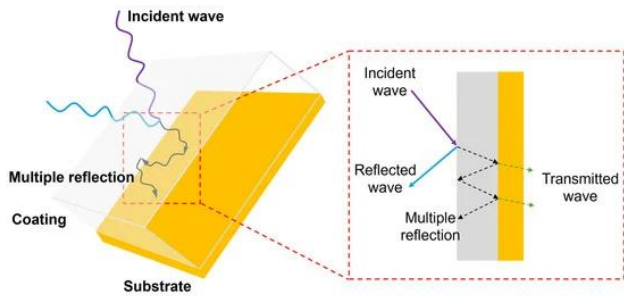

Figure 4.3: *Depiction of multiple reflections in a thin radar absorbing coating. The internal bouncing of incident waves boosts absorption efficiency, especially when the coating thickness is less than the skin depth (δ).*
[Reference:https://www.mdpi.com/2079-6412/14/5/607]

4.4 Feedstocks of EM Absorption Coatings

1. **Feedstocks** of EM (Electromagnetic) absorption coatings refer to the materials used to manufacture coatings that absorb and dissipate electromagnetic waves, reducing reflections and enhancing stealth or shielding properties. These coatings mainly consist of two essential components.
2. **Matrix Materials** – These provide structural support and help in dispersing the active EM absorbing materials.
3. **EM Absorbers** – These materials actively interact with electromagnetic waves to absorb and convert them into heat or other forms of energy.
4. **Matrices (Supporting Material)**
   I. **Polymer Matrices**: Epoxy resin, polyurethane (PU), polypropylene (PP), acrylic resin. Lightweight, flexible, and easy to process but less heat-resistant.
   II. **Ceramic Matrices**: Alumina (Al_2O_3), Silica (SiO_2), silicon carbide (SiC). Heat -resistant, oxidation-resistant, and commonly used in high-temperature environments.
5. **EM Absorbers (Active Material)**

   I. **Carbon-Based Absorbers**: Carbon nanotubes (CNTs), graphene, carbon black.High electrical conductivity, dielectric loss mechanism.
   II. **Magnetic Absorbers**: Ferrites, iron (Fe), cobalt (Co), nickel (Ni). Magnetic loss mechanism due to hysteresis and eddy current loss.
   III. **MXenes**: $Ti_3C_2T_x$ and other transition metal carbides/nitrides.Excellent conductivity, strong EM wave attenuation.

IV. **Metallic Composites**: Ni-SAs/NC, NiCoFe@C.Combine both dielectric and magnetic losses for improved absorption.

V. **MOFs (Metal-Organic Frameworks)**: NiFe@C, CoFe@C.Tunable porosity, lightweight, and strong absorption properties.

VI. **Metamaterials**: Gyroid-structured carbon, TPMS-shelled ceramics. Engineered to enhance absorption through structural design.

These feedstocks are selected based on their EM absorption properties, durability, weight, and application requirements (e.g., stealth technology, electromagnetic shielding).

4.5 Importance of Feedstocks in Anti-Radar Coating Development

Feedstocks play a crucial role in the development of anti-radar coatings, as they determine the efficiency, durability, and stealth capabilities of the material. These coatings rely on a combination of matrix materials and EM absorbers to reduce radar cross-section (RCS) and improve electromagnetic wave absorption. The selection of appropriate feedstocks directly impacts the coating's performance in stealth applications.

Key Roles of Feedstocks in Anti-Radar Coating Development

1. Enhanced Radar Absorption.
2. The EM absorbers (e.g., SiC, ZrC, CNTs, MXenes, ferrites) dissipate electromagnetic waves through dielectric and magnetic losses, minimizing radar reflection.
3. The right combination of matrix and absorber ensures that the coating's impedance matches that of free space, reducing signal reflection back to the radar.
4. Broadband Absorption Capability
5. Metallic composites and carbon-based materials allow the coating to absorb radar waves over a wide frequency range, making them effective against different radar bands (X-band, Ku-band, etc.).
6. High-Temperature and Environmental Stability
7. Ceramic-based matrices (e.g., Al_2O_3, SiC, SiO_2) provide oxidation resistance and thermal stability, ensuring the coating remains effective in harsh environments.
8. Lightweight and Durable Design
9. Polymer and ceramic matrices offer a balance of lightweight properties and mechanical strength, making them suitable for aircraft and military applications.
10. Multiple Reflection and Attenuation
11. Nanostructured materials (e.g., MXenes, MOFs, graphene) help in multiple reflections within the coating layers, enhancing wave dissipation before reaching the metal surface.
12. Customizability for Different Applications
13. Different feedstock compositions allow coatings to be tailored for specific stealth applications, such as aircraft, naval vessels, and military vehicles.

Kind of Absorbers	Name	$tan\delta\varepsilon$t	$tan\delta\mu$	Dominate Dissipation Mechanism	Typical Operating Frequencies (GHz)	RLmin	Reference
carbon materials	Fe/C hollow sphere	0.50~1.00	≈0.05	dielectric	6~18	−62.7	link
	N-CNTs encapsulated Co/Ni	0.05~0.55	−0.1~0.1	dielectric	6~10	−84.0	link
	Ag@SG	0.27~0.325	/	dielectric	9~12	−15	link
metallic composites	Ni-SAs/NC	0.20~0.60	≈0.0	dielectric	8~14	−36.4	link
	Co1+Cs/NGC	0.30~0.75	≈0.0	dielectric	10~18	−54.3	link
	MXene/polyaniline	0.2~1.2	0.0~0.4	dielectric	5~11	−60.6	link
	NiCoFe@C	≈0.33	0.07~0.15	dielectric and magnetic	9~11	−47.6	link
	Ni/Ni3ZnC0.3	0.5~1.5	0.05~0.2	dielectric and magnetic	12~18	−56.8	link
	Zn-HHTP	0.16~0.23	/	dielectric	2~10	−62.8	link
	MOF@MOF	0.20~0.95	−0.3~0.3	dielectric	10~18	−40	link
ferromagnetic materials	RGO@FGT	0.4~1.0	−0.2~0.15	dielectric and magnetic	11~14	−61	link

	P[AVIm][HoCl4]/rGO	**0.2~0.35**	**0.05~0.25**	**magnetic**	**10.5−15.6**	**−57.32**	link
Metamaterials	**gyroid structured carbon-based material**	**/**	**/**	**dielectric**	**2~40**	**−40**	link
	TPMS-Shellular structured SiOC ceramics	**0.41~0.56**	**/**	**dielectric**	**12~18**	**−72.38**	link -

Table 4.1: *Comparison of various radar absorbing materials (RAMs) based on their type, dissipation mechanisms, loss tangents* ($\boldsymbol{tan\delta\varepsilon}$t, $\boldsymbol{tan\delta\mu}$), *operating frequency ranges, and minimum reflection loss (RLmin). The table highlights both dielectric and magnetic loss contributions and their effectiveness across different GHz ranges.*

5. Methodology

5.1 Sintering Process for Pellet Preparation

5.1.1 Material Selection & Powder Preparation:

1. The selected materials for plasma spray are SiC/Al_2O_3 and ZrC/Al_2O_3, while for cold spray, $SiC/Al_2O_3/Al$ and $ZrC/Al_2O_3/Al$ are used.
2. The ceramic powders are mixed using ball milling or mechanical mixing to achieve a homogeneous blend.

5.1.2 Compaction (Pellet Formation):

1. The mixed powders are compressed into pellets using either:
2. Uniaxial pressing (pressure: 100-300 MPa).
3. Cold Isostatic Pressing (CIP) (pressure: 200-500 MPa).
4.This step ensures the formation of green pellets with proper density and uniformity.

5.1.3 Sintering Process:

1.The green pellets are subjected to high-temperature sintering in a controlled atmosphere (argon/nitrogen) to enhance densification.

2.The sintering temperature is set as follows:

2.1.1 Plasma Spray Materials: 1600-1800°C

2.1.2 Cold Spray Materials: 1400-1600°C (lower due to Al content)

3.If hot pressing is used, an additional 20-50 MPa pressure is applied during sintering to improve grain bonding and densification.

5.1.4 Controlled Cooling:

1.The sintered pellets undergo controlled furnace cooling to minimize internal stresses and prevent cracks.

5.1.5 Quality Assessment:

1.The final pellets are evaluated for:

1.1.1 Density & porosity measurement

1.1.2 Microstructural analysis

2.This step ensures the reliability and consistency of the prepared pellets for further coating processes.

5.1.6 Final Prepared Pellets: The sintered pellets are now ready for coating via plasma spray or cold spray techniques.

6. Techniques of Coating for Radar Absorbing Materials (RAMs)

Radar Absorbing Materials (RAMs) are used to reduce radar reflections and improve stealth properties. Here are some commonly used coating techniques for RAM applications:

6.1 Plasma Spray Coating

6.1.1 Process:

Uses a high-temperature plasma jet to melt and spray ceramic or metal-based RAM powders onto the surface.

Forms a dense and adherent coating with controlled thickness.

6.1.2 Advantages: High thermal stability

Strong adhesion to substrates

Suitable for complex surfaces

6.1.3 **Common Materials**: Ferrite-based ceramics (SiC/Al_2O_3, ZrC/Al_2O_3)

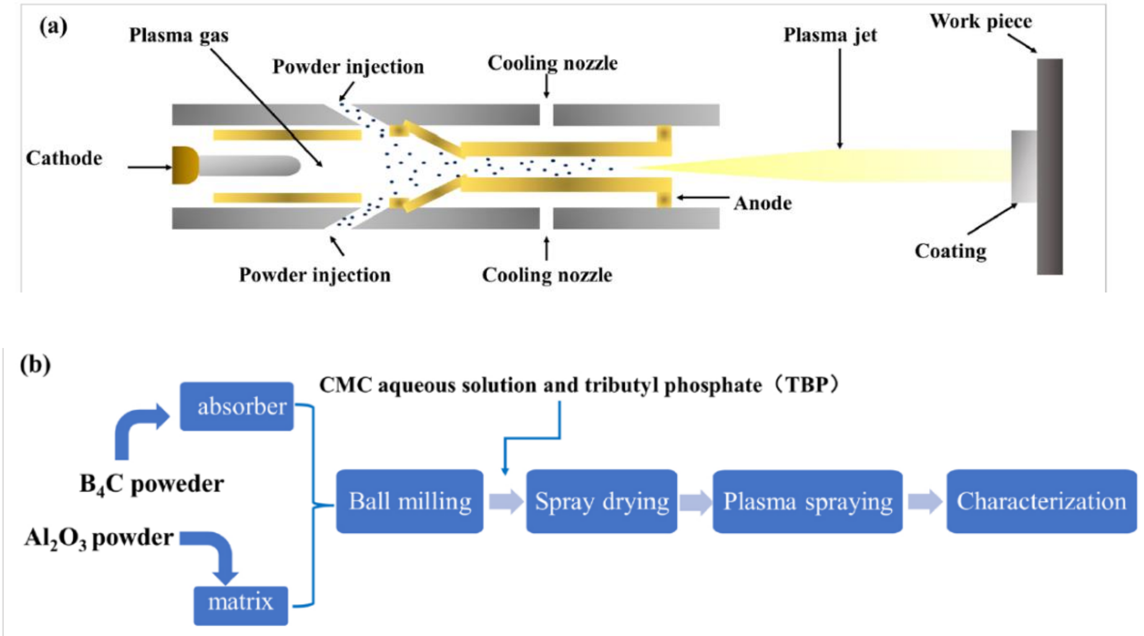

Figure 6.1: The schematic diagram of a) plasma torch, b) the preparation process of plasma spray coating

[Reference:https://www.sciencedirect.com/science/article/abs/pii/S0955221922009293?casa_token=sCpva_Rfrl8AAAAA:PA8p3dgc-RTu7_CfuU-1-aVpi3jIbZ3gi6-9OQO9Ej8_6_mA9Hb6OQXUxZSgRjXgBAGjiJzvAghh]

6.2 Cold Spray Coating

6.2.1 **Process**:

Uses a supersonic gas jet to accelerate powder particles, which impact and bond mechanically without melting.

Reduces oxidation and maintains material properties.

6.2.2 **Advantages**:

Low thermal impact (no phase change)

Strong mechanical bonding

High deposition efficiency

6.2.3 **Common Materials**: Metal-ceramic RAM composites ($SiC/Al_2O_3/Al$, $ZrC/Al_2O_3/Al$)

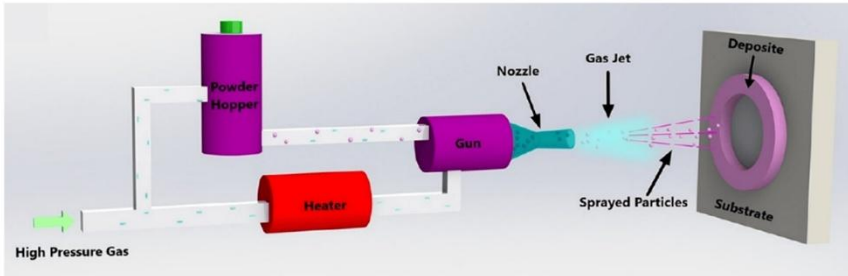

Figure 6.2: *Schematic of the cold spray coating process. A high-pressure gas accelerates powder particles through a nozzle at supersonic speeds, enabling mechanical bonding onto a substrate without melting. This technique preserves material properties and ensures strong adhesion, making it ideal for depositing metal-ceramic RAM composites such as SiC/Al_2O_3/Al and ZrC/Al_2O_3/Al.*

[Reference:https://www.mdpi.com/2079-6412/14/7/822#B44-coatings-14-00822]

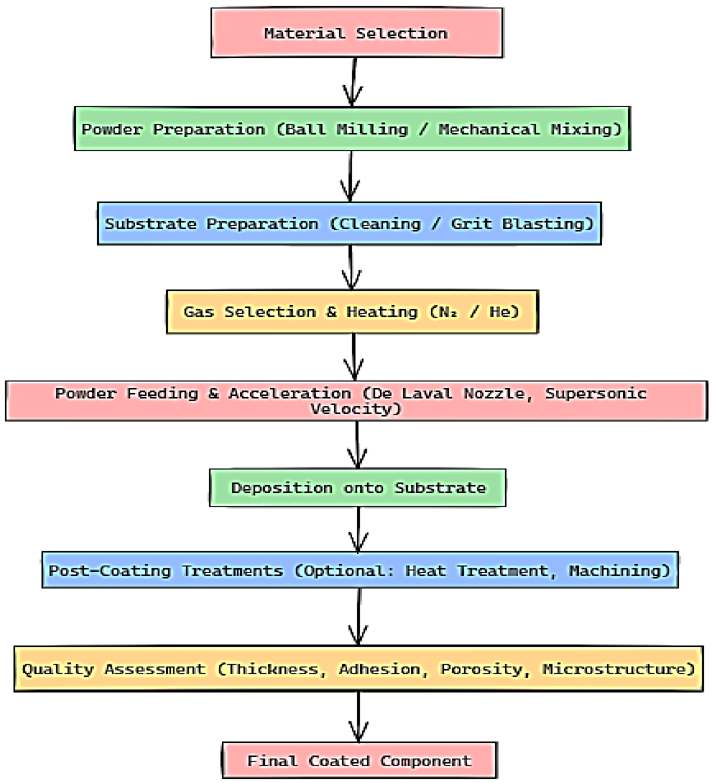

Figure 6.3: *Workflow of the cold spray coating process. The procedure begins with material and powder preparation, followed by substrate cleaning, gas selection, and powder acceleration through a De Laval nozzle. The coating is deposited onto the substrate and may undergo post-treatment before final quality assessment to ensure optimal coating performance.*

6.3 Chemical Vapor Deposition (CVD)

6.3.1 Process:

Gaseous precursors react on the heated substrate to form a thin RAM coating.

Allows for uniform coating at the nanoscale.

6.3.2 **Advantages**:

Excellent uniformity.

High purity and controlled thickness.

Good adhesion and durability.

6.3.3 **Common Materials**: Carbon-based RAMs, Metal Oxides.

6.4 Physical Vapor Deposition (PVD)

6.4.1 Process:

Uses evaporation or sputtering to deposit a thin RAM layer on the substrate in a vacuum chamber.

Provides precise thickness control.

6.4.2 **Advantages**:

Thin and uniform coating

Good adhesion and corrosion resistance

Suitable for high-precision applications

6.4.3 **Common Materials**: Ferrite RAMs, Conductive Polymers

6.5 Electroless Plating

6.5.1 **Process**:

Uses a chemical reaction to deposit a metal or composite RAM coating without electricity.

Creates a smooth, conductive RAM layer.

6.5.2 **Advantages**:

Uniform deposition on complex surfaces

Cost-effective for large-scale production

Suitable for composite materials

6.5.3 **Common Materials**: Ni-P, Ni-B alloys, Metal Oxide RAMs

6.6 Spray Coating (Polymer-Based RAMs)

6.6.1 **Process**:

Liquid RAMs (conductive polymers or ferrite composites) are sprayed onto surfaces and cured.

Used for flexible coatings.

6.6.2 **Advantages**:

Simple and scalable

It can be applied to flexible substrates.

Good electromagnetic absorption

6.6.3 **Common Materials**: Conductive polymers, Ferrite-graphene composites.

7. Best Coating Technique for Our Radar Absorbing Material (RAM)

Since our materials include SiC/Al_2O_3, ZrC/Al_2O_3 for Plasma Spray and $SiC/Al_2O_3/Al$, $ZrC/Al_2O_3/Al$ for Cold Spray, the best techniques are:

7.1 Plasma Spray Coating (For SiC/Al_2O_3, ZrC/Al_2O_3)

1. High-temperature plasma allows strong adhesion of ceramic RAM.
2. Forms a thick and dense coating, improving absorption.
3. Suitable for high-heat applications and wear-resistant surfaces.
4. Limitations:
    1. Can induce thermal stresses due to high processing temperature.
    2. Might require post-processing to reduce porosity.

7.2 Cold Spray Coating (For $SiC/Al_2O_3/Al$, $ZrC/Al_2O_3/Al$)

1. Low-temperature process prevents oxidation or phase change.
2. Strong mechanical bonding without melting the material.
3. Suitable for metal-ceramic RAM composites with an aluminum matrix.
4. Limitations:
    1. May require post-processing for enhanced density.
    2. Lower deposition efficiency compared to plasma spray.

7.3 Final Recommendation:

1. Plasma Spray is best for high-performance ceramic-based RAM coatings.

2. Cold Spray is ideal for metal-ceramic composites to maintain properties without thermal degradation.

7.4 Selection Criteria for Coating Technique:

Technique	Best for	Thermal Impact	Coating Thickness	Durability
Plasma Spray	High-temp ceramics	High	Thick	High
Cold Spray	Metal-ceramic RAMs	Low	Medium	High
CVD	Thin-film RAMs	Medium	Very Thin	High
PVD	Precision coatings	Medium	Very Thin	High
Electroless Plating	Metal RAMs	Low	Thin	Medium
Spray Coating	Flexible RAMs	Low	Thin	Medium

Table 7.1: *Comparison of various coating techniques based on their suitability for different RAM applications, thermal impact, achievable coating thickness, and durability. This assists in selecting the most appropriate technique for specific performance requirements*

7.5 Bonding Mechanism:

Figure 7.1 image explains the bonding mechanism in cold spray coating (shown for ZrC,Cu):

1. **Initial Impact (a, b):** High-velocity particles (ZrC, Cu) impact the substrate, breaking the oxide film and increasing surface roughness.
2. **Mechanical Interlocking (c):** Some particles rebound, while others embed and interlock with the surface.
3. **Deposition & Compaction (d):** Repeated impacts cause deformation, flattening, and compaction, closing pores and enhancing bonding.
4. **Final Coating (e, f):** A dense coating forms with entrapped particles and deformed splats, ensuring strong adhesion to the substrate.

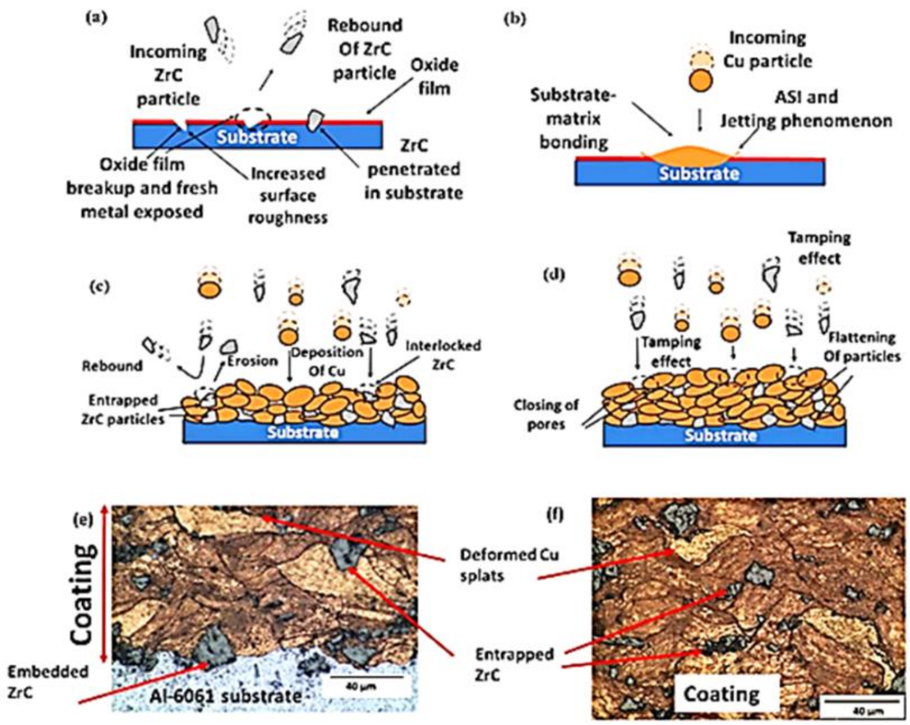

Figure 7.1: *Schematic and microstructural representation of the bonding mechanism in cold spray coating for ZrC/Cu composites. The process involves (a–b) initial impact breaking the oxide film, (c) mechanical interlocking of particles, (d) deposition and compaction to close pores, and (e–f) formation of a dense coating with embedded and deformed particles ensuring strong adhesion.*

[Reference:https://www.sciencedirect.com/science/article/abs/pii/S0030399224016293?casa_token=_S7un1fqME0AAAAA:5DFsRVihnYuch81EfNQ0YORLuIrSRTKZt7Ak6bIYIySyXoCP7TblNIsAV7nW7RrZtP6xi10EmAFJ]

8. EXPERIMENTAL METHODOLOGY

8.1 APPARATUS REQUIRED

Figure 8.1: Manual Pellet Maker, **Figure 8.2:** Ball Mill

Figure 8.3: Thermal Cycling Machine TM-1200 **Figure 8.4:** Mettler Toledo

8.2 MATERIALS REQUIRED:

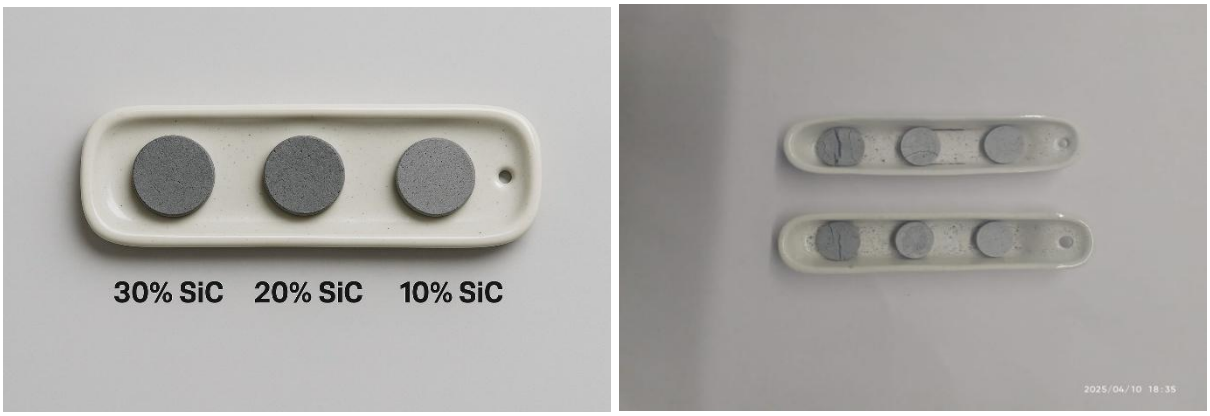

Figure 8.5: Green (left) and Sintered (right) Samples

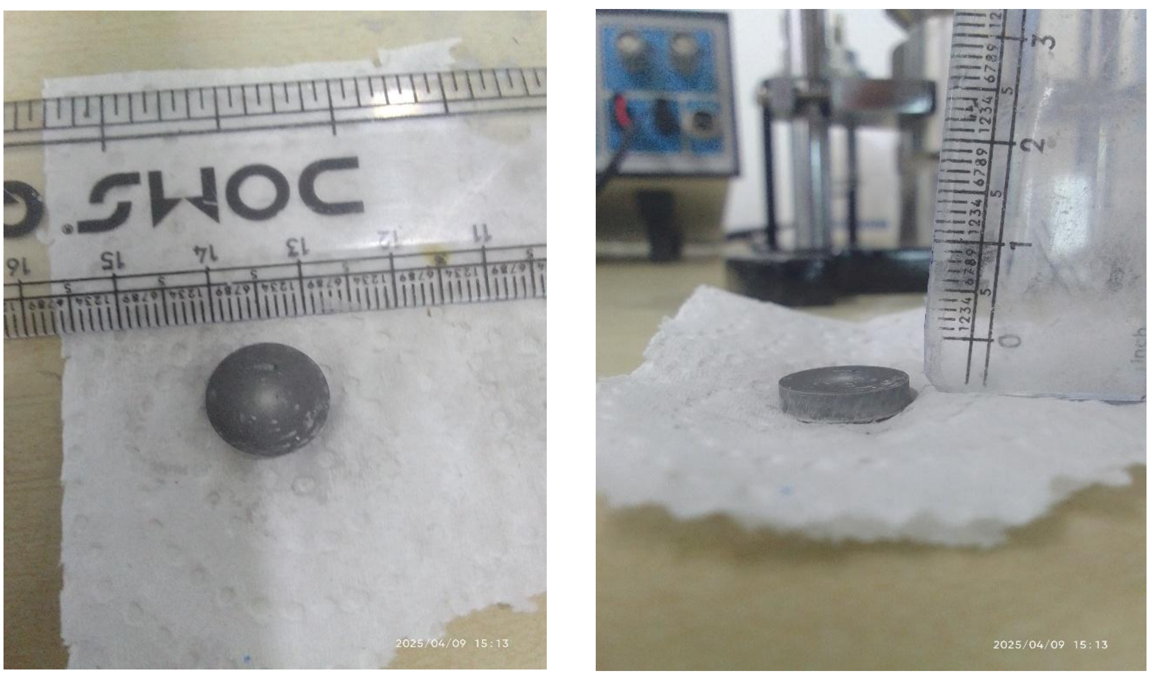

Figure 8.5: Sizing the Sample

Material	Purpose	Grade / Purity
Silicon Carbide (SiC)	Reinforcement phase in ceramic composite	>99% purity, powder form
Zirconium Carbide (ZrC)	Reinforcement phase in alternate composite	>99% purity, powder form
Alumina (Al_2O_3)	Primary ceramic matrix material	α-phase, >99% purity
Aluminum (Al)	Metallic binder / conductivity enhancer	Fine powder, >99% purity
Polyvinyl Alcohol (PVA)	Binder for pellet compaction (optional)	Analytical grade
Isopropyl Alcohol	Used for wet milling and cleaning purposes	AR grade

Table 8.1: *List of raw materials used in composite preparation along with their respective purposes and purity/grade specifications, including reinforcement phases, binders, and processing aids.*

8.3 Properties of Materials

Material	Chemical Formula	Density (g/cm³)	Melting Point (°C)	Hardness (Mohs)	Thermal Conductivity (W/m·K)	Electrical Conductivity	Thermal Expansion ($\times 10^{-6}$/K)	Radar Absorption Role
Silicon Carbide (SiC)	SiC	~3.2	~2730	9–9.5	120–270	Semi-conductor (P-type)	~4.0	Dielectric loss, impedance matching
Zirconium Carbide (ZrC)	ZrC	~6.73	~3530	8–9	20–33	High (Metallic)	~6.6	Conduction & reflection loss
Aluminum Oxide (Al_2O_3)	Al_2O_3	~3.95	~2072	~9	~30	Insulator	–	Stable ceramic matrix, dielectric loss
Aluminum (Al)	Al	~2.7	~660	–	~235	Excellent (~37.8 MS/m)	–	Enhances conductivity & bonding
Polyvinyl Alcohol (PVA)	$(C_2H_4O)n$	~1.19	~200 (decomp	–	–	Non-conductive	–	Temporary binder (burns off)

Table 8.2: *Key physical properties of materials used in the composite system, such as density, melting point, hardness, thermal and electrical conductivity, thermal expansion, and their respective roles in radar absorption.*

8.4 PROCESS FLOW

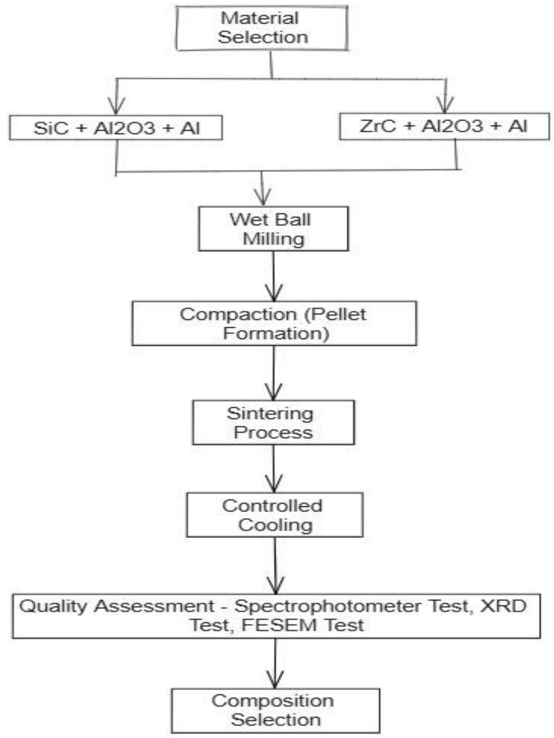

Figure 8.6: *Schematic process flow for composite synthesis, illustrating steps from raw material selection (SiC/ZrC, Al_2O_3, Al) to powder mixing, pellet compaction, sintering, controlled cooling, and final quality assessment using spectrophotometric, XRD, and FESEM tests.*

Raw Material Selection: High-purity Al_2O_3, Al and varying percentages of SiC and ZrC powders are selected.

Powder Mixing: The powders are weighed according to the desired composition (e.g., 30%, 20%, 10% SiC) and mixed thoroughly to ensure homogeneity.

Pellet Formation: The mixed powders are compacted into pellets using a uniaxial press, with or without a binder.

Sintering: The green pellets are sintered at high temperature under controlled atmospheric conditions to achieve densification.

Characterization: The sintered pellets are analysed using FESEM and XRD to study microstructure and phase composition.

This process flow enables systematic preparation and evaluation of ceramic composites with varying SiC content for advanced applications.

9.RESULTS & DISCUSSION

9.1 FESEM RESULTS

9.1.1 FESEM ANALYSIS OF 10% SiC, 10%Al, & 80% Al2O3:

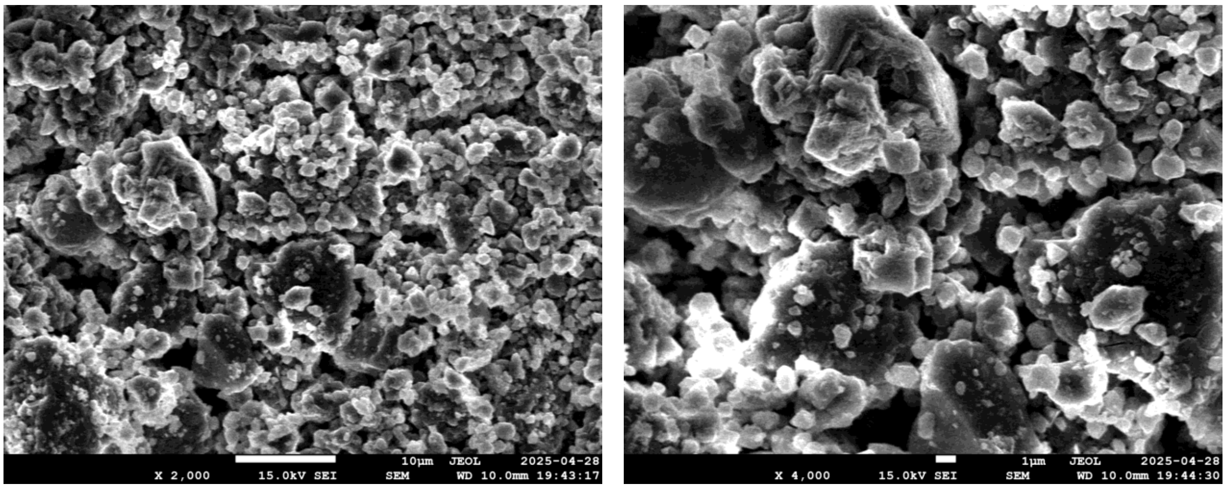

Figure 9.1: SEM micrographs showing morphology of 10% SiC +10% Al + 80% Al2O3 (ceramics) at magnification (a) x2000 and (b) x4000.

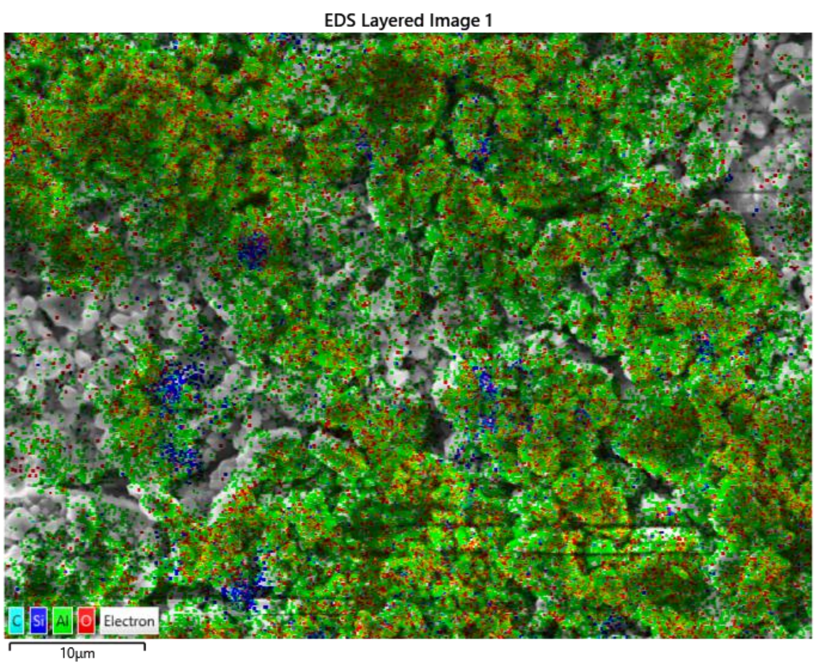

Figure 9.2: Cross-sectional SEM and EDS mappings.

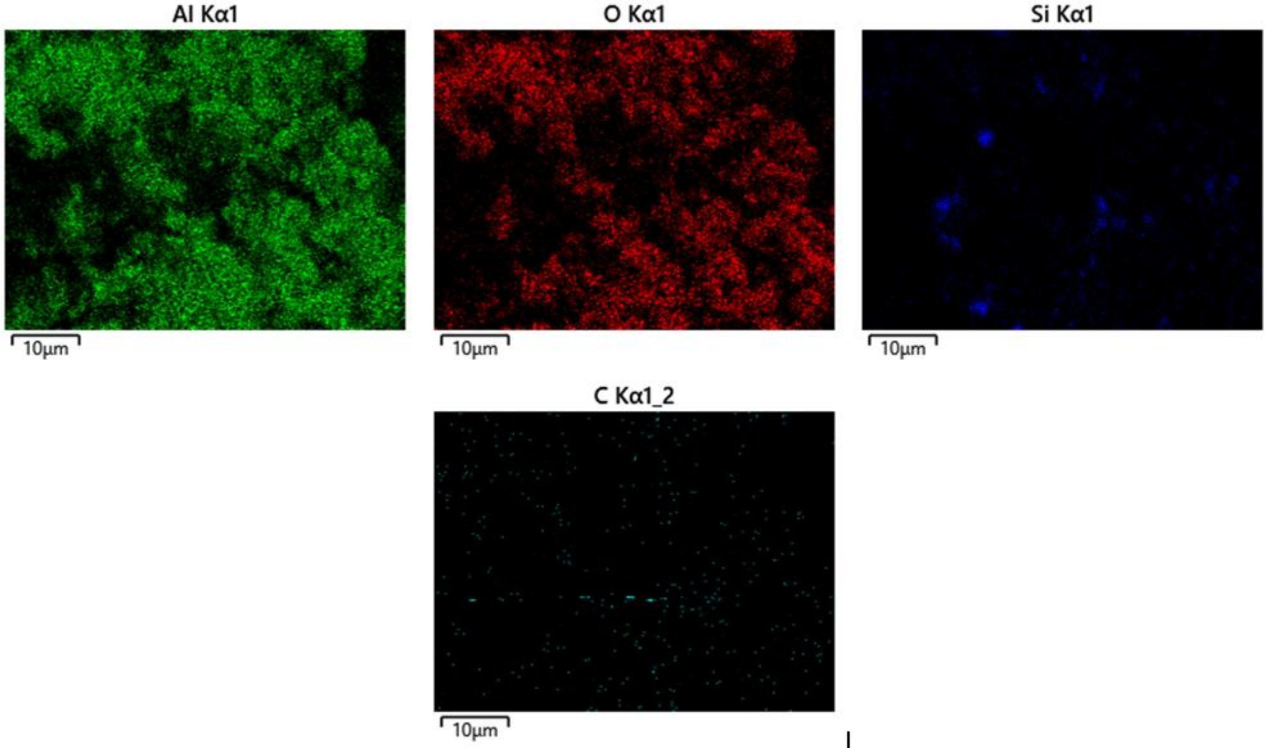

Figure 9.3: Cross-sectional SEM and EDS mappings.

9.1.2 FESEM FOR 20% SiC, 10% Al, & 70% Al2O3

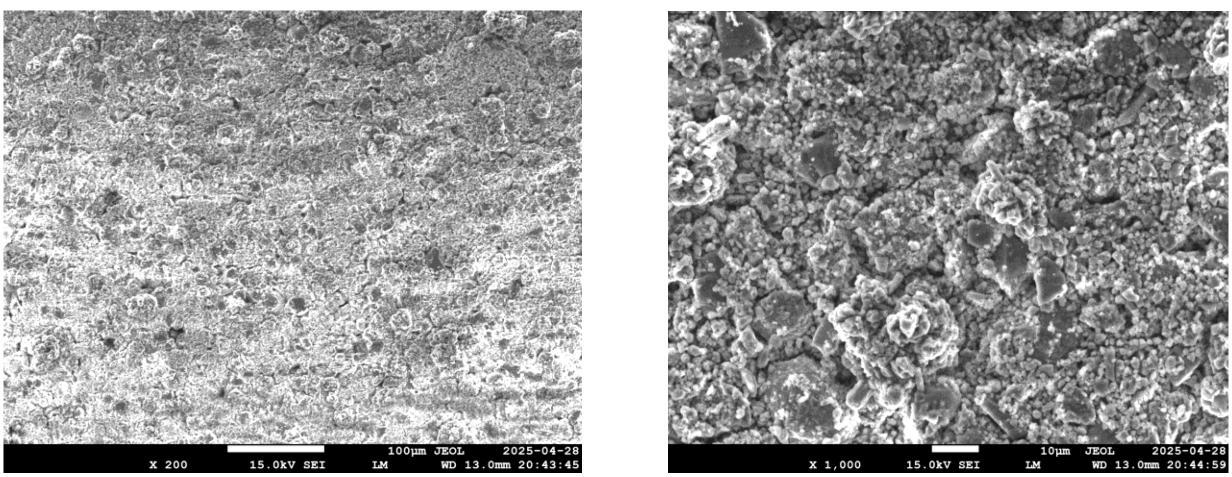

Fig 9.4 SEM micrographs showing morphology of 20% SiC + 10% Al + 70% Al2O3 (ceramics) at magnification (a) x200 and (b) x1000.

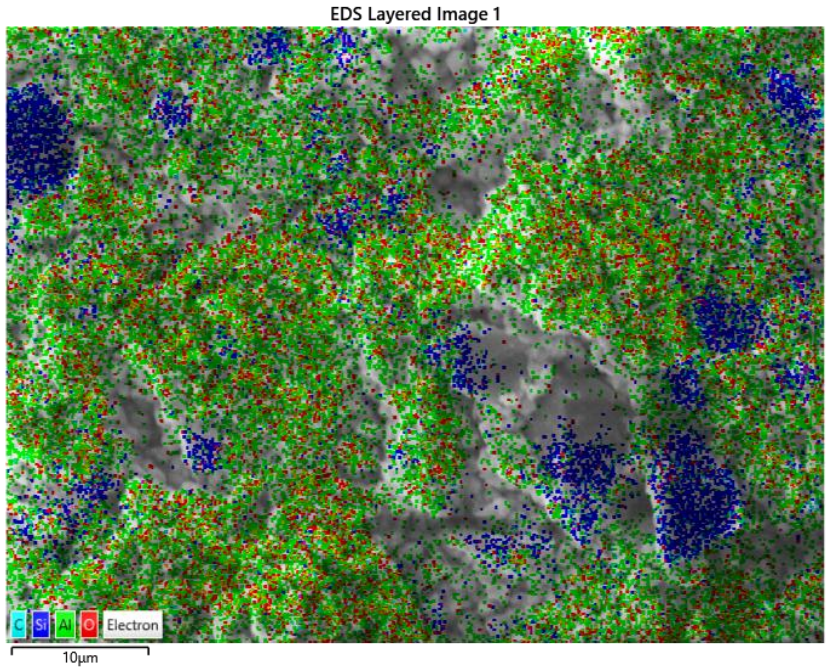

Figure 9.5: Cross-sectional SEM and EDS mappings

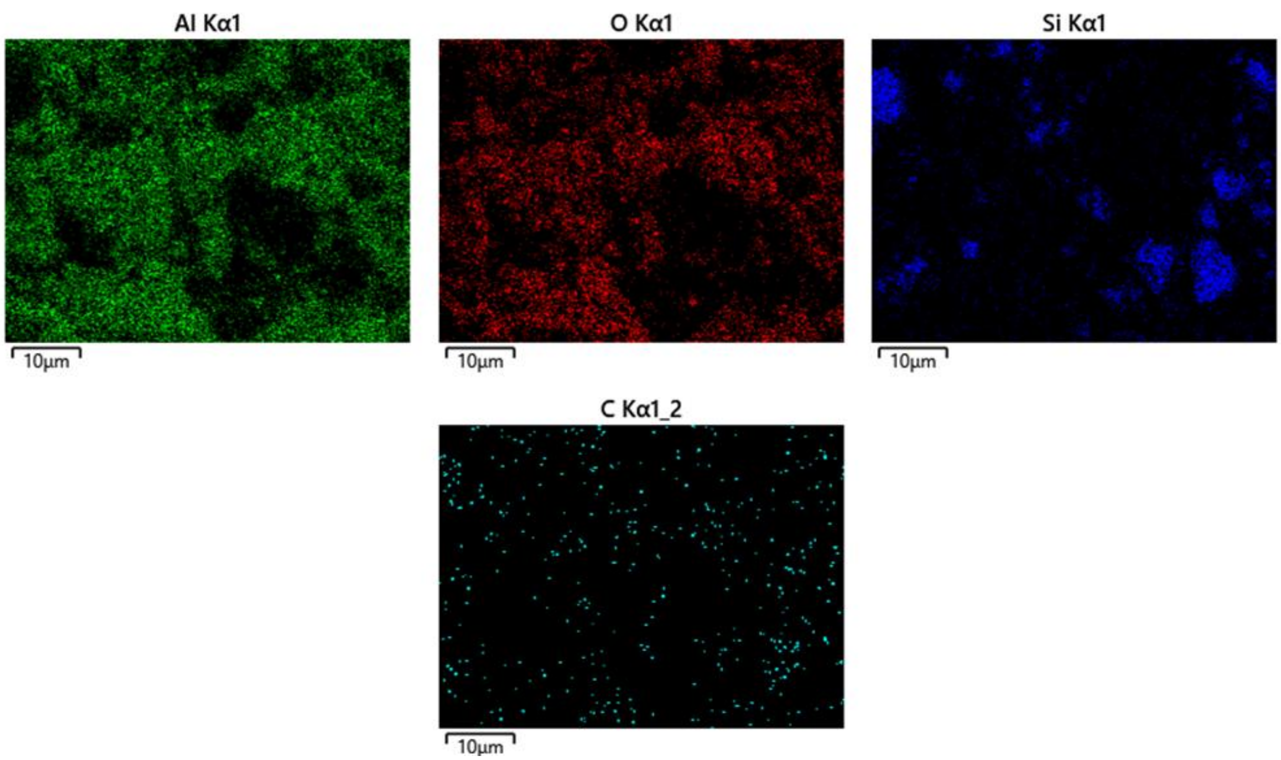

Figure 9.6: Cross-sectional SEM and EDS mappings

9.1.3 FESEM FOR 30% SiC, 10% Al, & 60% Al2O3

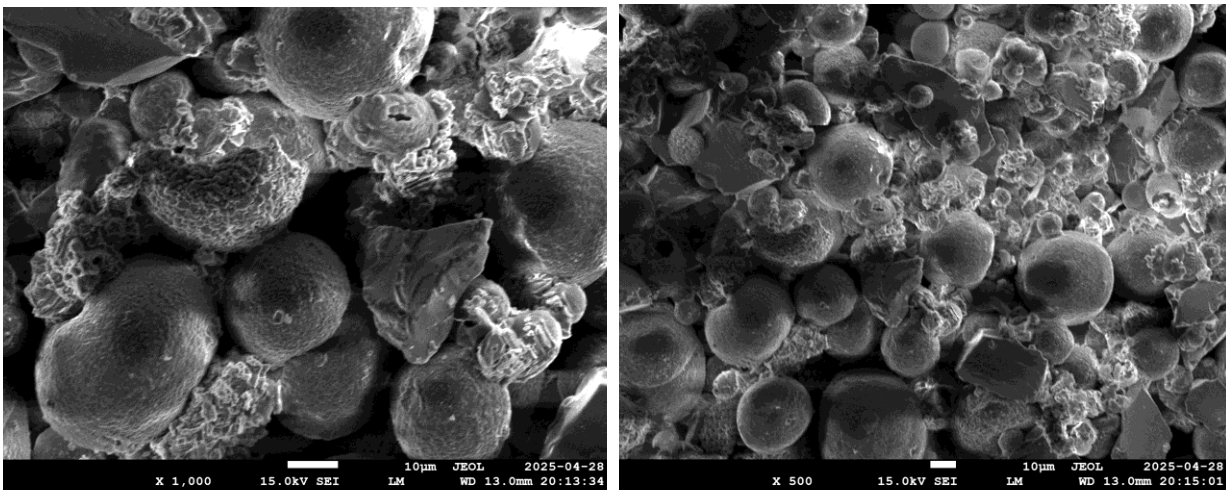

Figure 9.7: SEM micrographs showing morphology of 30% SiC + 10% Al + 70% Al2O3 (ceramics) at magnification (a) x1000 and (b) x500.

9.1.4 FESEM FOR 10% ZrC, 10% Al, & 80% Al2O3

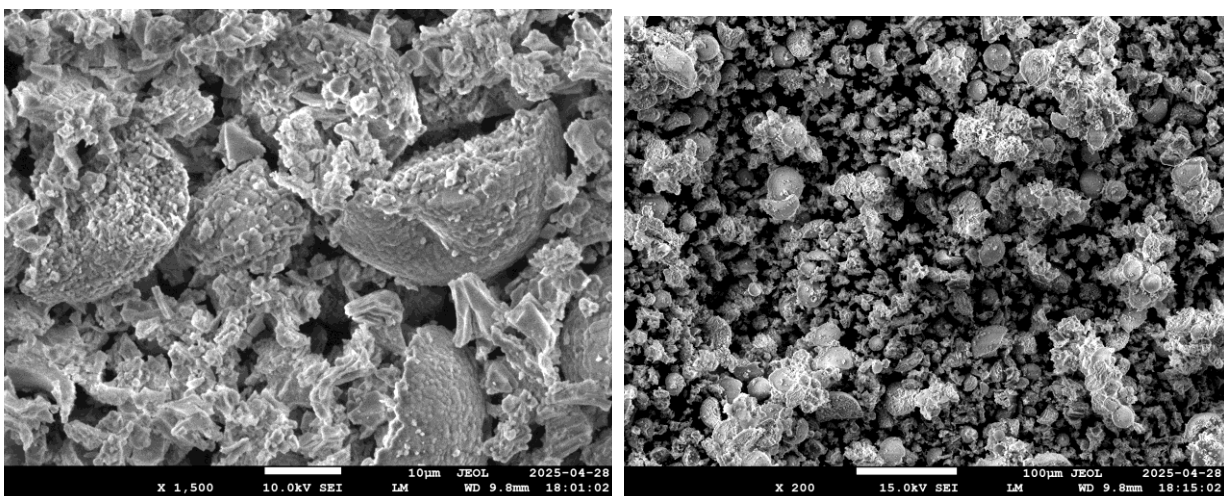

Figure 9.8: SEM micrographs showing morphology of 10% ZrC + 10% Al + 80% Al2O3(ceramics) at magnification (a) x1500 and (b) x200.

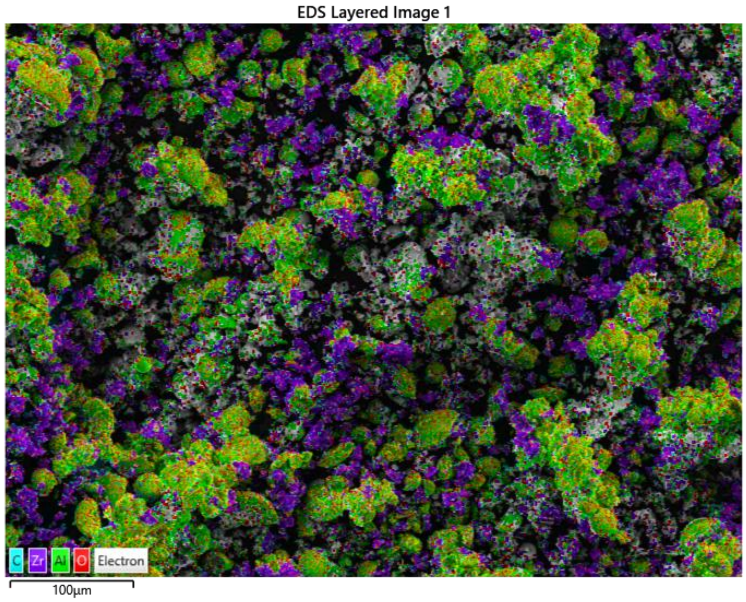

Figure 9.9: Cross-sectional SEM and EDS mappings

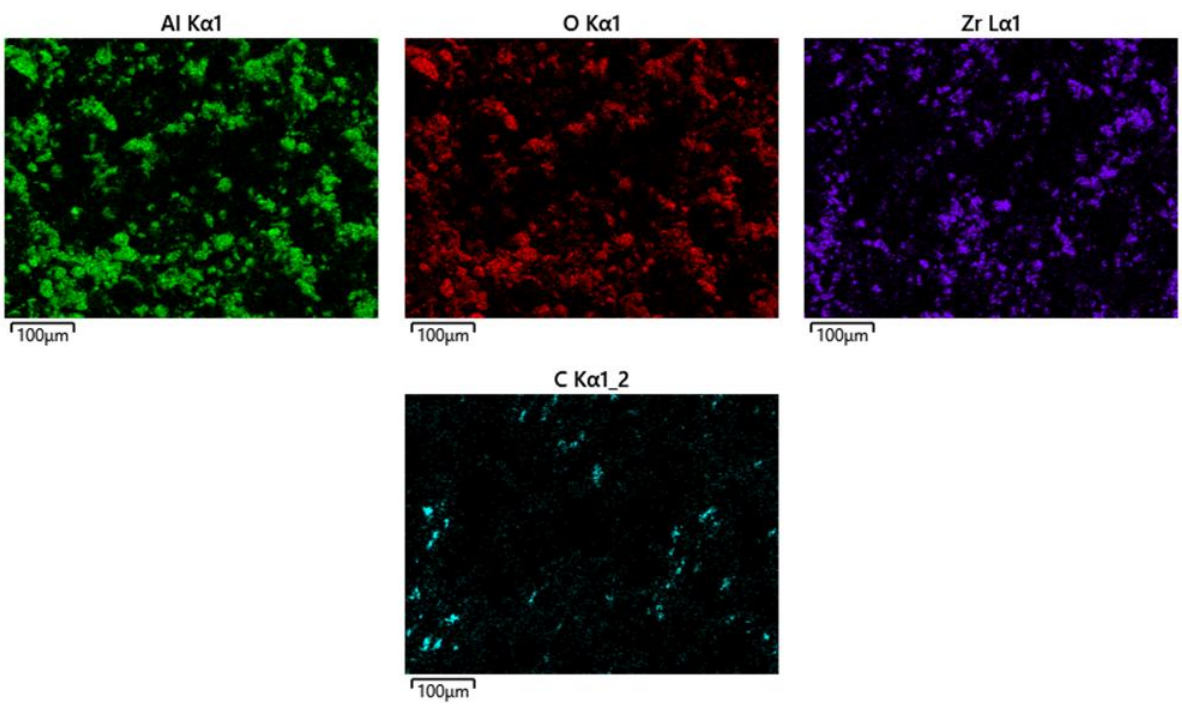

Figure 9.10: Cross-sectional SEM and EDS mappings

9.1.5 FESEM FOR 20% ZrC, 10% Al, & 70% Al2O3

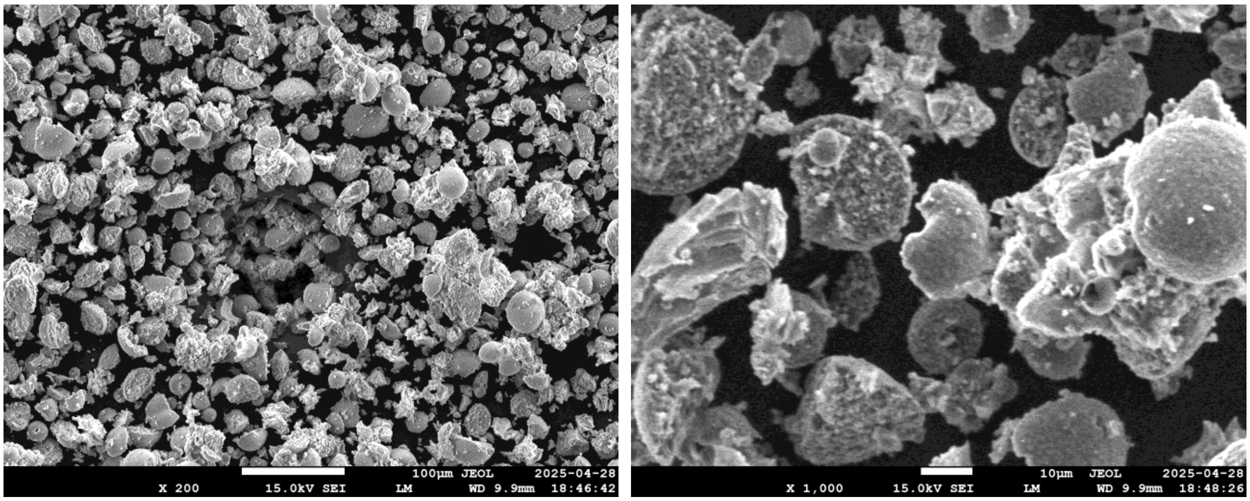

Figure 9.11: SEM micrographs showing morphology of 20% ZrC + 10% Al + 70% Al2O3(ceramics) at magnification (a) x200 and (b) x1000.

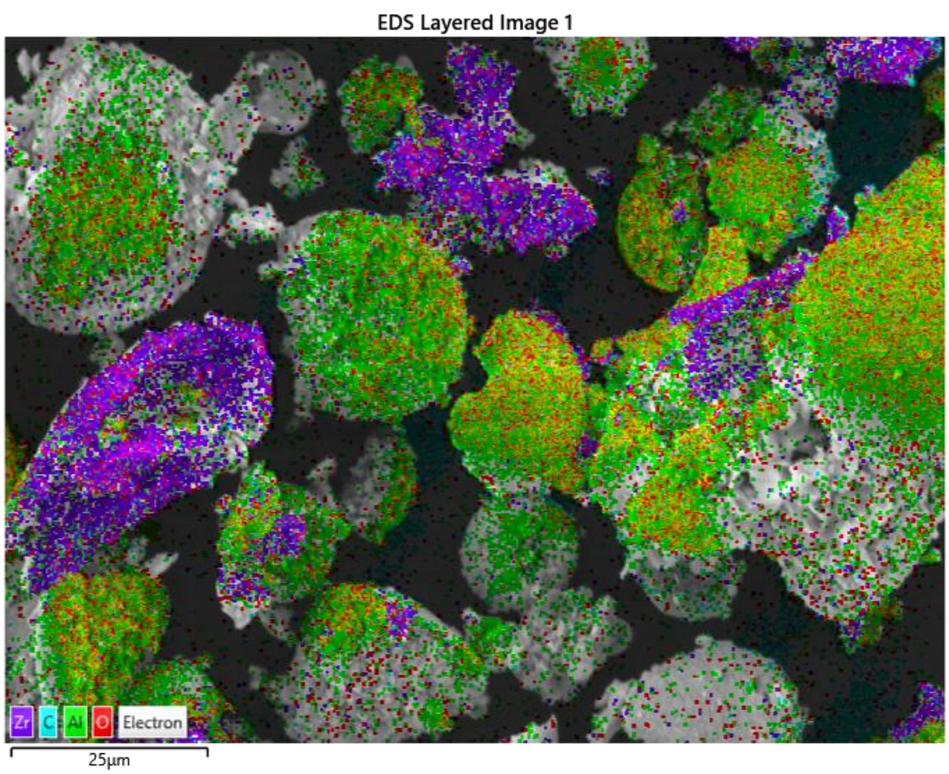

Figure 9.12: Cross-sectional SEM and EDS mappings.

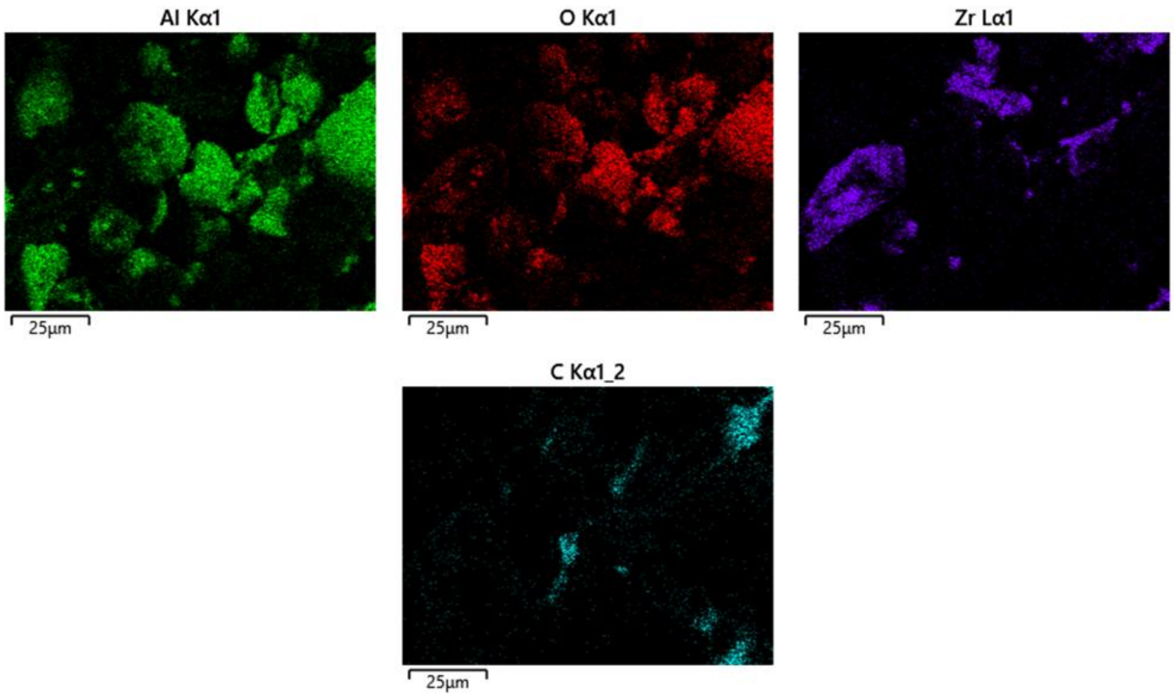

Figure 9.13: Cross-sectional SEM and EDS mappings.

9.1.6 FESEM FOR 30% ZrC, 10% Al, & 60% Al2O3

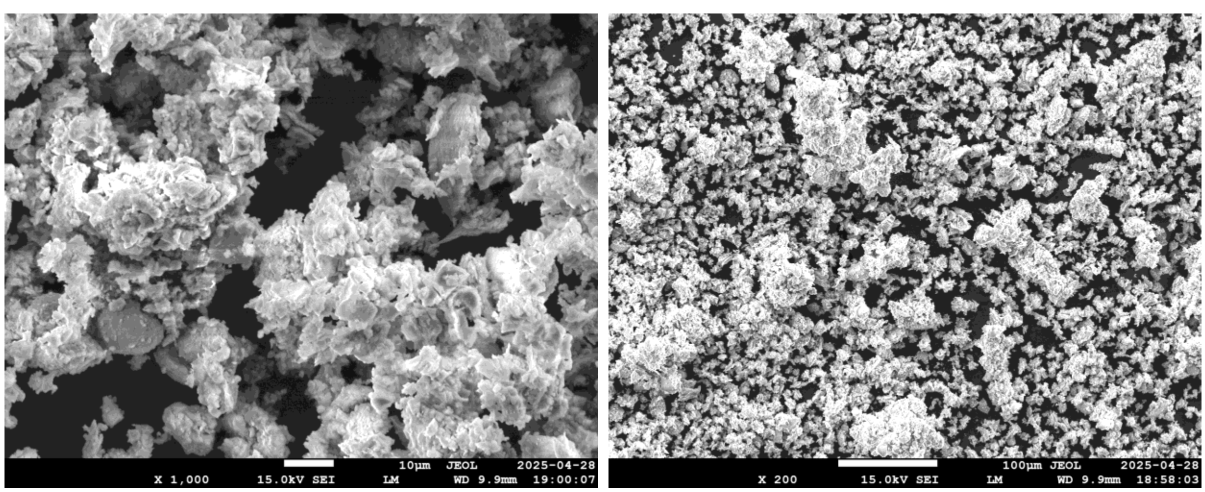

Figure 9.14: SEM micrographs showing morphology of 30% ZrC + 10% Al + 60% Al2O3 (ceramics) at magnification (a) x1000 and (b) x200.

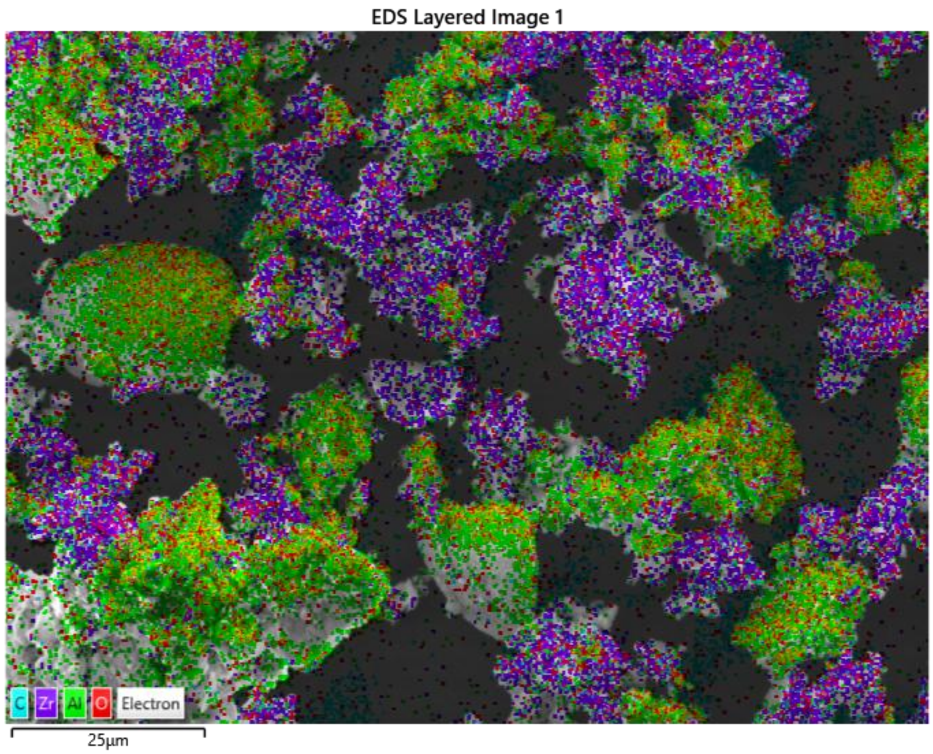

Figure 9.15: Cross-sectional SEM and EDS mappings.

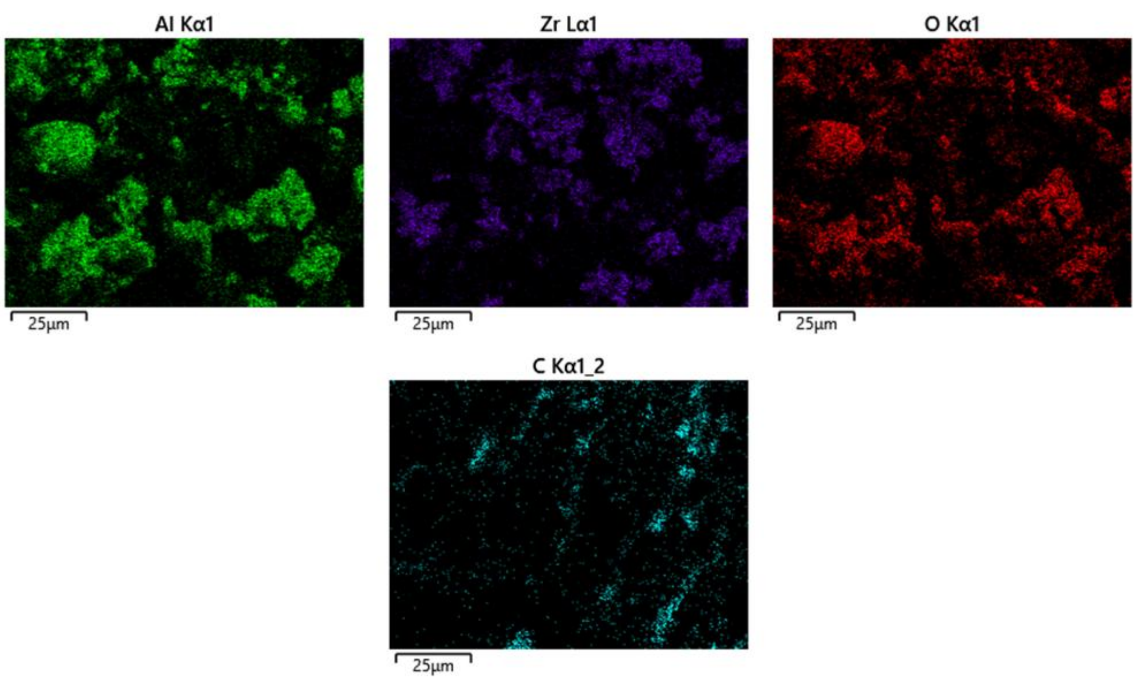

Figure 9.16: Cross-sectional SEM and EDS mappings.

9.1.7 FESEM Analysis

9.1.7.1 Microstructural and Elemental Analysis of Composite Coatings

To evaluate the surface morphology and elemental distribution of the developed ceramic composite coatings, Field Emission Scanning Electron Microscopy (FESEM) and Energy-Dispersive X-ray Spectroscopy (EDS) analyses were conducted. The samples analyzed include SiC + Al_2O_3 and ZrC + Al_2O_3 composites with varying reinforcement content: 10%, 20%, and 30% by weight.

9.1.7.2 FESEM Analysis

The FESEM images reveal the microstructural characteristics of the coatings for different compositions.

SiC + Al_2O_3 Composites: With increasing SiC content, a more refined and densely packed microstructure was observed. At 10% SiC, the dispersion appears relatively uniform, while at 30%, agglomeration of SiC particles was visible, suggesting clustering due to higher concentration. The micrographs highlight the ceramic matrix's granular morphology with embedded SiC particles acting as reinforcement.

ZrC + Al_2O_3 Composites: Similar trends were noted with ZrC. At lower content (10%), the microstructure remained homogeneous. As the ZrC content increased, regions of densified clusters were seen. ZrC's higher density compared to SiC also influenced particle packing and interparticle spacing.

These images collectively demonstrate that the reinforcement type and content significantly influence the surface texture, porosity, and bonding nature of the coating. Higher reinforcement may lead to improved hardness but can also cause localized inhomogeneity.

9.1.7.3 EDS Analysis

The EDS spectra confirmed the presence of respective elements in each sample:

For SiC + Al_2O_3, prominent peaks for Si, C, Al, and O were detected, validating successful incorporation of silicon carbide into the alumina matrix.
For ZrC + Al_2O_3, peaks for Zr, C, Al, and O were seen. The Zr signal intensity increased with increasing ZrC content, correlating well with the compositional design.

Quantitative EDS data indicated the expected elemental ratios close to the targeted compositions, confirming uniform distribution for lower percentages and slightly skewed concentration in 30% due to particle agglomeration.

9.2 XRD RESULTS

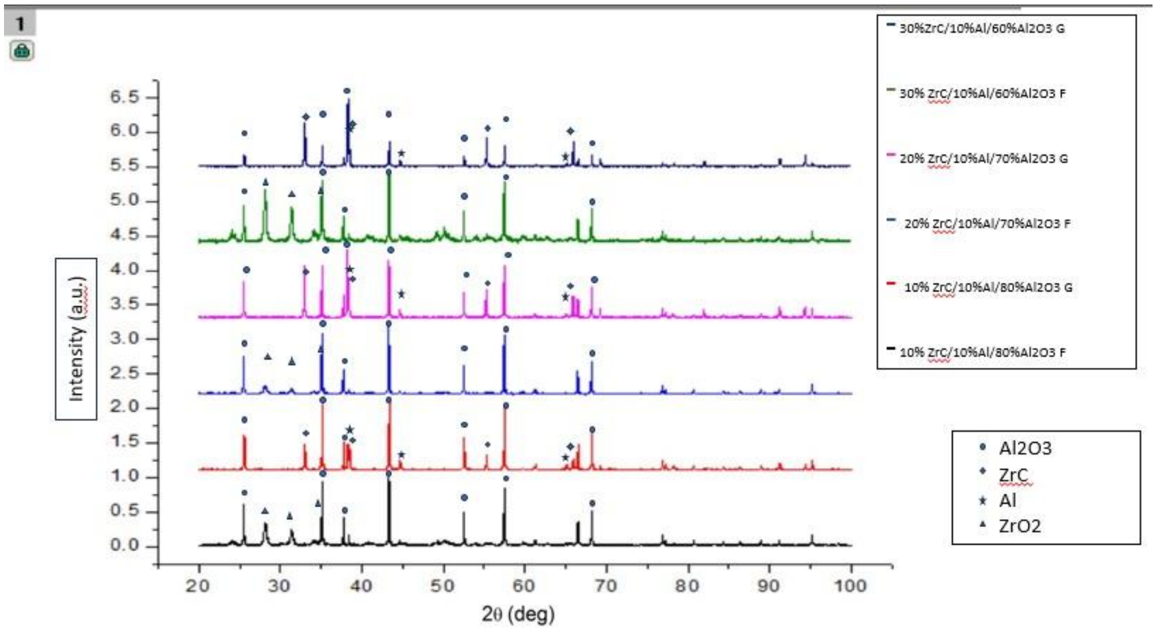

Figure 9.17: XRD analysis of the SiC and Al2O3 (green & sintered pellets) feedstock, SiC-10%Al2O3, SiC-20% Al2O3, SiC-30% Al2O3.

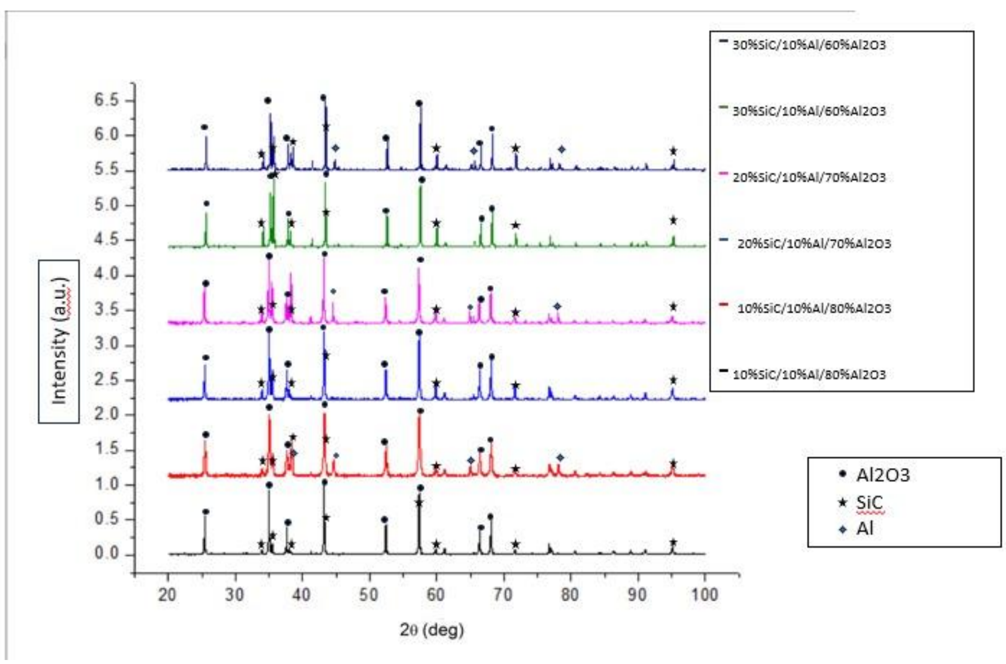

Figure 9.18: XRD analysis of the ZrC and Al2O3 (green pellet & sintered powder) feedstock, ZrC-10%Al2O3, ZrC-20% Al2O3, ZrC-30% Al2O3.

9.2.1 X-Ray Diffraction (XRD) Analysis of SiC–Al_2O_3–Al Ceramic Composites

8.1.1 X-ray Diffraction (XRD) analysis was carried out to study the phase composition of SiC–Al_2O_3–Al ceramic composites with 10%, 20%, and 30% SiC content. The results, shown in Figure 1, provide insights into phase retention and structural stability post-sintering.

8.1.2 Al_2O_3 Peaks: Intense and sharp diffraction peaks of α-Al_2O_3 confirm its dominance as the primary ceramic phase and its stability throughout the processing.

8.1.3 SiC Peaks: SiC peaks were identified at their characteristic 2θ values, and their relative intensities increased proportionally with SiC content. The absence of peak distortion suggests SiC remained chemically stable during sintering.

8.1.4 Aluminum Peaks: Distinct but less intense peaks for metallic Al were observed, indicating the presence of elemental aluminum retained in the composite. These may contribute to improved thermal or electrical conductivity and aid in composite densification.

Phase Stability: No evidence of undesirable reaction products (e.g., aluminum silicates or spinels) was found, signifying good compatibility among SiC, Al_2O_3, and Al.
The XRD patterns confirm the successful synthesis of a multi-phase ceramic composite system, with all constituents—SiC, Al_2O_3, and Al—maintaining their individual identities and structural integrity**.**

9.2.2 X-Ray Diffraction (XRD) Analysis of ZrC–Al_2O_3–Al Ceramic Composites

9.2.2.1 XRD was also performed for ZrC–Al_2O_3–Al ceramic composites with 10%, 20%, and 30% ZrC to examine their phase composition and thermal compatibility.

9.2.2.2 Al_2O_3 Peaks: Strong diffraction peaks of α-Al_2O_3 were present in all compositions, indicating that it remains the stable base phase of the composite.

9.2.2.3 ZrC Peaks: Characteristic ZrC peaks were clearly detected, and their intensities increased with higher ZrC percentages. The peak positions matched well with standard ZrC patterns, confirming phase retention after sintering.

9.2.2.4 Aluminum Peaks: Metallic Al peaks were also visible, confirming its survival through the sintering process without complete oxidation or reaction. This indicates its potential role as a conductive or toughening agent.

Reaction Absence: The lack of intermediate phases (such as zirconates or aluminates) confirms the thermochemical stability of the ZrC–Al_2O_3–Al system under the applied conditions.
Overall, the XRD analysis verifies that the ZrC–Al_2O_3–Al composites preserve all three phases in their crystalline form and exhibit high phase purity—ideal for high-temperature, stealth, or EM absorption applications.

9.3 SPECTROPHOTOMETER RESULTS

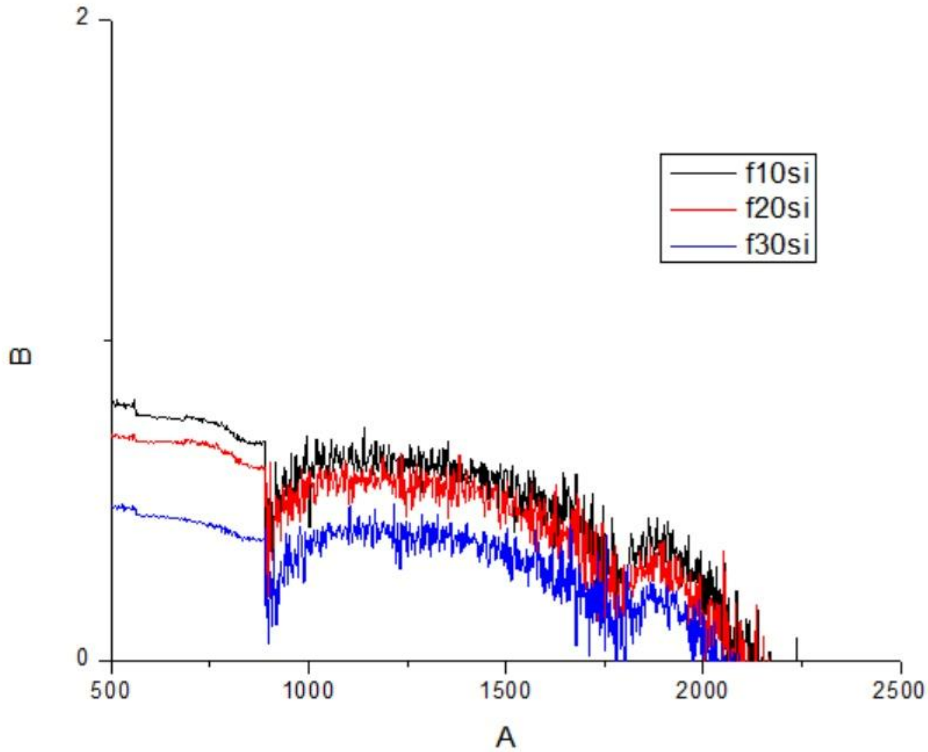

Figure 9.19: Spectrophotometer Reflection Test for SiC–Al_2O_3 Composites

Reflectance spectra of composite samples containing varying SiC content: f10si (10% SiC, 90% Al_2O_3), f20si (20% SiC, 80% Al_2O_3), and f30si (30% SiC, 70% Al_2O_3). The X-axis (A) represents the wavelength (in nanometers), and the Y-axis (B) represents the reflectance intensity (arbitrary units). The results show that increasing the SiC content leads to a decrease in reflectance, indicating improved light absorption characteristics with higher SiC proportions.

Spectrophotometer Reflection Test – Analysis

- The reflection spectra of SiC–Al_2O_3 composites with varying SiC content (10%, 20%, 30%) show a decreasing trend in reflectance as SiC percentage increases.
- This indicates that:Higher SiC content improves absorption characteristics, reducing the intensity of reflected electromagnetic waves.
- The composite with 30% SiC exhibits the lowest reflectance, making it the most effective in radar absorption.
- This result aligns with the goal of developing efficient stealth coatings, where minimal reflection is desired for reduced radar visibility.

Out of $SiC/Al_2O_3/Al$ and $ZrC/Al_2O_3/Al$ we found out best is $SiC/Al_2O_3/Al$. Below is Table 9.1 showing results

Test / Property	$SiC–Al_2O_3–Al$	$ZrC–Al_2O_3–Al$	Which is Better?	Why?
FESEM	Dense, uniform, low porosity	Heterogeneous, some agglomerates	$SiC–Al_2O_3–Al$	Better uniformity and densification
XRD	Phase purity, good interface	Minor secondary phases possible	$SiC–Al_2O_3–Al$	Phase stability and interface bonding
Mechanical Properties	High hardness, wear resistance	Improved with dispersion	$SiC–Al_2O_3–Al$	Consistent improvement, better at high temperature
Oxidation Resistance	Excellent	Poorer	$SiC–Al_2O_3–Al$	SiC is more stable in oxidizing environments
High Temp. Stability	High	Lower (oxidation risk)	$SiC–Al_2O_3–Al$	SiC maintains properties at high temperature
Density	Lesser	Higher	$SiC–Al_2O_3–Al$	ZrC (6.59 g/cm³) is much denser than SiC (3.21 g/cm³)

Table 9.1 ***Comparative analysis of $SiC–Al_2O_3–Al$ and $ZrC–Al_2O_3–Al$ composites based on microstructure, phase stability, mechanical and thermal properties, oxidation resistance, and density. $SiC–Al_2O_3–Al$ outperforms in most categories.***

Further if we compare three samples of $SiC/Al_2O_3/Al$ namely (30%SiC + 60%Al_2O_3+10%Al), (20%SiC + 70%Al_2O_3+10%Al), (10%SiC + 80%Al_2O_3+10%Al); we found out that 30%SiC + 60%Al_2O_3+10%Al is best. Below Table 9.2 is the showing the results

Test / Property	10% SiC	20% SiC	30% SiC	Best Composition
FESEM (Microstructure)	Fine grains, some porosity, moderate densification	Denser, better grain connection, less porosity	Densest, tightly packed grains, minimal porosity	30% SiC
XRD (Phase Analysis)	Clear SiC and Al_2O_3 peaks, phase purity	Stronger SiC peaks, phase purity maintained	Strongest SiC peaks, excellent phase stability	30% SiC
Spectrophotometer (Optical)	Moderate reflectance, improved absorption	Stronger SiC peaks, phase purity maintained	Lowest reflectance, highest absorption	30% SiC

Table 9.2 ***Performance evaluation of $SiC–Al_2O_3–Al$ composites with varying SiC content (10%, 20%, 30%) in terms of microstructure (FESEM), phase purity (XRD), and optical properties (Spectrophotometer). The 30% SiC composition shows optimal performance across all tested properties.***

10. Future Work

Evaluation and Enhancement of Coatings Developed by Plasma Spray and Cold Spray Techniques

This study aims to evaluate the performance, stability, and effectiveness of coatings applied using Plasma Spray and Cold Spray (Coldspray) techniques, especially under real service conditions. These advanced coating methods are widely used in aerospace, defense, and industrial applications where durability, thermal protection, and radar absorption are critical. To ensure reliability in these applications, it is important to thoroughly test the coatings after application.

First, the **durability and adhesion strength** of the coatings will be assessed. This involves simulating real-world working conditions such as exposure to mechanical loads, thermal cycling, friction, and environmental stress. The goal is to understand how well the coatings stay attached to the base material over time and how resistant they are to cracking, peeling, or erosion during use.

Second, the **effect of multilayer coating structures** will be studied. Multilayer coatings can combine materials with different properties in a single structure, offering better performance than single-layer coatings. For example, one layer may provide high hardness, while another improves thermal insulation or radar absorption. By optimizing the layer arrangement and thickness, it may be possible to significantly improve mechanical strength, thermal resistance, and stealth capability against electromagnetic waves.

In addition, the research will **explore new compositions and dopants** to enhance coating properties. Doping the base material with specific elements or compounds can increase **thermal stability, surface hardness**, or the ability to absorb electromagnetic radiation. Materials with improved heat resistance are particularly important in high-temperature environments such as jet engines or exhaust systems.

The study will also include **long-term aging and corrosion resistance tests**. These will simulate harsh environmental conditions like high humidity, salt spray (to replicate marine environments), and frequent temperature cycling. The aim is to evaluate how the coating behaves over extended periods and whether it maintains its protective qualities in corrosive or fluctuating climates.

Finally, **microstructural analysis** will be performed to observe how the coating evolves under stress. Techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) will be used to examine structural changes at the microscopic level. This will help identify the key **degradation mechanisms**, such as crack formation, phase changes, or interfacial delamination, which can affect long-term performance.

Overall, this comprehensive evaluation will support the development of next-generation coatings that offer excellent durability, thermal and mechanical resistance, and radar absorption.

11. Conclusion

This project focused on the fabrication and analysis of ceramic composites using varying compositions of ZrC, Al_2O_3, SiC, and Al. Throughout the experimental process, challenges such as pellet formation failure and post-sintering disintegration were encountered. These issues highlighted the importance of proper binder usage, adequate compaction pressure, and a controlled sintering environment. Despite some failures, valuable insights were gained regarding the behavior of different materials during processing. Moving forward, implementing improvements such as binder addition and sintering in inert atmospheres can significantly enhance the quality and structural stability of the composites. Overall, the project contributed to a better understanding of ceramic composite fabrication and provides a solid foundation for further optimization and study.

Through an in-depth literature review, we explored various traditional and emerging stealth materials, ultimately identifying SiC/Al_2O_3 and ZrC/Al_2O_3 as highly promising candidates due to their superior dielectric properties, thermal stability, adhesion strength, and radar absorption capabilities. Additionally, we studied different deposition techniques, such as Plasma Spray for ceramic-based coatings and Cold Spray for metal matrix composite coatings, both of which are widely used in aerospace and defence applications.

To ensure effective stealth performance, we also examined critical characterization techniques like X-ray Diffraction (XRD) for analyzing the crystalline structure and Scanning Electron Microscopy (SEM) for studying the microstructure and surface morphology. These techniques are essential for evaluating the coating's efficiency in reducing radar reflection and improving adhesion strength.
This research serves as a strong foundation for future experimental studies, enabling further optimization of stealth coatings through practical implementation and testing. The insights gained from this study will be beneficial for advancing stealth technology, particularly in enhancing the radar invisibility of aircraft and other defense-related applications.

12. Reference

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