Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 5, No.4, May : 2025

IN SITU ALUMINIUM METAL MATRIX COMPOSITES SYNTHESIZED BY TITANIUM SULPHIDE APPROACH

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ABSTRACT
Aluminium metal matrix composites have a huge potential in aerospace and automotive industries due to its high specific strength and modulus. The mechanical properties of these MMCs largely depend on the size, distribution and wettability of particles on the matrix. With finer, uniformly distributed and better wetted particles, the yield strength of the MMCs also increase. With conventional stir casting, achieving uniform dispersion of fine ceramic particles is a challenging task due to agglomeration of particles by Vander Waals force of attraction. Most of the challenges in the processing of nano-composites can be overcome by solid lubricating properties in-situ approach.The main objective of this project is to successfully fabricate Aluminium356 based in-situ metal matrix composites reinforced with various Percentage of TIS2 particles by assisted squeeze casting and to characterize the microstructure and mechanical properties. Aluminium356 was used as the matrix material and TIS2(TITANIUM DI SULPHIDE) was used as the Reinforcement Powder. Four types of in-situ composites were processed under four different processing volumes such as 10% ,20%, 30%.

Keywords:
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INTRODUCTION
1.1 General Introduction
In the previous phase of our project, we successfully fabricated aluminium based in-situ metal matrix composites using ultrasonication- assisted squeeze casting. The main objective of this project is to fabricate aluminium356-based in-situ metal matrix composites reinforced with Inorganic compound of TiS2 particles by assisted squeeze casting, and to characterize their microstructure and mechanical properties. Aluminium 356 was used as the matrix material, and TiS2 (Titanium di Sulphide) was used as the Organic Compound. Four types of in-situ composites were processed at four different Volumes under 10g, 20g,30g.

In-situ fabrication of MMCs is a promising approach that allows the reinforcement phase to form directly within the metal matrix during processing, leading to better interfacial bonding, cleaner interfaces, and improved particle distribution compared to conventional ex-situ methods. Titanium Disulfide (TiS_2), a solid lubricant with a layered structure and excellent thermal and mechanical stability, serves as an effective reinforcement material. When formed or introduced in-situ, TiS_2 contributes significantly to the enhancement of wear resistance and mechanical performance of the composite.

This project focuses on the in-situ fabrication of A356–TiS_2 composites using advanced casting techniques. The goal is to synthesize a uniform dispersion of TiS_2 within the A356 matrix while ensuring strong interfacial bonding, ultimately improving the composite's hardness, strength, and tribological behavior. The process involves controlled synthesis conditions to facilitate in-situ formation and effective integration of TiS_2 particles within the aluminium matrix.


Aluminium 356 Titanium Di Sulphide

1.2 Applications of A356 – TiS_2 Metal Matrix Composites

1. Automotive Industry

○ **Brake rotors and pads**: The wear resistance and lubricating nature of TiS_2 make the composite ideal for reducing friction and improving lifespan.

○ **Engine components** (pistons, cylinder liners): Enhanced strength and thermal stability allow the material to withstand high-temperature environments.

○ **Suspension parts**: The lightweight yet high-strength nature of the composite contributes to improved fuel efficiency and durability.

2. Aerospace Industry

○ **Structural components**: High strength-to-weight ratio is crucial in aerospace, and TiS_2-reinforced A356 provides both mechanical integrity and reduced weight.

○ **Bearing and bushing materials**: Solid lubrication properties of TiS_2 reduce maintenance needs and friction under extreme conditions.

3. Industrial Applications

○ **Wear-resistant tooling**: Ideal for parts that experience constant sliding or abrasive contact.

○ **Pump and valve components**: Corrosion resistance and thermal stability make it suitable for handling fluids or gases under pressure and temperature.

4. Marine Applications

○ **Propeller shafts and marine bearings**: Corrosion resistance of A356, combined with TiS_2's stability, makes it suitable for saltwater environments.

5. Electronic and Thermal Management Devices

○ **Heat sinks and casings**: Good thermal conductivity, lightweight nature, and stability make it viable for electronic enclosures and cooling elements.

1.3 Problem Faced and Challenges

1. Achieving Uniform Dispersion of TiS_2 Particles:

- **Agglomeration:** TiS_2 particles, especially in fine powder form, have a tendency to clump together due to van der Waals forces. This can lead to non- uniform distribution within the aluminum matrix, resulting in localized areas with high reinforcement concentration and others with little to none. This non- uniformity can negatively impact the overall mechanical properties and wear resistance.
- **Density Difference:** The significant density difference between aluminum (around 2.7 g/cm^3) and titanium disulfide (around 3.22 g/cm^3) can cause settling or segregation of the TiS_2 particles within the molten metal, especially during the melting and solidification stages. This can lead to a gradient in reinforcement concentration throughout the cast component.

- **Wetting Issues:** Achieving good wetting between the molten aluminum and the TiS_2 particles is crucial for strong interfacial bonding. Poor wettability can lead to weak interfaces, porosity, and reduced load transfer efficiency, ultimately weakening the composite.

2. Controlling the Interfacial Reaction:

- **Formation of Brittle Intermetallics:** At high temperatures and over extended periods (even within the 50-60 minute window), there's a possibility of chemical reactions occurring at the interface between the aluminum matrix and the TiS_2 reinforcement. These reactions can form brittle intermetallic compounds, which can be detrimental to the composite's toughness and ductility. Careful control of melting temperature and holding time is essential to minimize such reactions.

3. Managing Porosity:

- **Gas Entrapment:** During the melting and stirring process, gases can get entrapped in the molten metal, leading to porosity in the final cast component. Porosity reduces the effective load-bearing area and can significantly weaken the composite. Degassing procedures are often necessary but might not be entirely effective.
- **Shrinkage during Solidification:** Aluminum alloys undergo significant shrinkage during solidification. The presence of reinforcement particles can hinder the flow of the liquid metal, potentially leading to shrinkage porosity, especially in complex shapes.

4. Ensuring Reproducibility and Process Control:

- **Maintaining Consistent Melting Conditions:** Achieving consistent melting temperatures and holding times within the 50-60 minute window across different batches can be challenging. Fluctuations in these parameters can affect the microstructure and properties of the resulting composites.
- **Accurate Reinforcement Addition:** Precisely adding and uniformly dispersing the desired amounts of TiS_2 (10, 20, and 30 grams for a specific base amount of Al 356) requires careful measurement and a controlled addition process. Errors in this step will lead to variations in the composite composition and properties.

5. Challenges in Testing and Characterization:

- **Sample Preparation:** Preparing homogeneous and defect-free samples for mechanical testing (tensile, hardness) and microstructural analysis (SEM) from the composite material can be more challenging compared to monolithic metals due to the presence of the reinforcement phase.
- **Interpreting SEM Images:** Analyzing the distribution and interfacial bonding of the reinforcement particles in SEM images can sometimes be complex, requiring expertise in materials science and microscopy. Distinguishing between well-bonded and poorly bonded interfaces can be subjective.

Wear Test Variability: Wear test results can be sensitive to various factors, including the surface finish of the samples, the counter material used, and the environmental conditions. Ensuring consistent and reliable wear test data requires careful control of these parameters.

LITERATURE SURVEY

An extensive survey of available literature was carried out, and the summary of the literature review is presented .

2.1 ALUMINIUM MATRIX COMPOSITES

Yadav et al. (2023)

Title: Microstructure and Mechanical Properties of an In Situ Al356-Mg_2Si-TiB_2 Hybrid Composite Prepared by Stir and Cooling Slope Casting.

Key Findings: The incorporation of Mg_2Si and in-situ formed TiS_2 particles led to refined microstructures and improved mechanical properties. The cooling slope technique facilitated dendrite fragmentation, resulting in spherical and non-dendritic structures. The hybrid composite exhibited enhanced tensile strength, ductility, and hardness compared to conventional stir-cast composites.

Aluminium 356 alloy is a widely used **hypoeutectic aluminum-silicon casting alloy** known for its excellent castability, good corrosion resistance, weldability, and relatively high strength-to-weight ratio. Its typical composition includes around 6.5-7.5% silicon, 0.25-0.45% magnesium, and small amounts of other elements like iron, copper, and manganese, with the balance being aluminum.

Due to its attractive properties, A356 is frequently used as a **matrix material** in Metal Matrix Composites (MMCs). By reinforcing the A356 alloy with various ceramic or metallic particles, fibers, or whiskers, its mechanical, thermal, and tribological properties can be significantly enhanced and tailored for specific applications.l.

2.3 Mechanical Properties:

- **Strength and Stiffness:**

Reinforcements significantly improve the tensile strength and elastic modulus of aluminum MMCs. Example: Studies by showed a 20-30% increase in tensile strength with 10% TiS_2 reinforcement in Aluminum 356.

- **Wear Resistance:**

Research highlights a substantial improvement in wear properties with ceramic reinforcements. observed a reduction in wear rate by 50% compared to pure aluminum alloys.

- **Fatigue Performance:**

Enhanced resistance to cyclic loading, as reported in ,makes aluminum MMCs ideal for automotive engine components.

2.6 Process Parameter Optimization for Al-356/TiS_2

In our experimental study, four Aluminium 356 samples were machined using wire EDM under varying parameters to evaluate cutting performance. The samples were processed with increasing discharge currents (6A, 8A, 10A, and 12A) while maintaining a constant pulse-on time of 60µs and dielectric flushing pressure of 0.6 kg/cm². Results demonstrated a direct correlation between current intensity and machining characteristics - higher currents (10-12A) yielded a 28% greater material removal rate (MRR) compared to lower currents (6-8A), but simultaneously increased surface roughness from 2.4µm to 4.1µm (Ra). Sample 3 (10A) exhibited optimal balance with an MRR of 18.7 mm³/min and acceptable Ra of 3.2µm, while Sample 4 (12A) showed signs of thermal overloading including micro-cracks and a 15% wider kerf. Electrode wear followed a non-linear trend, peaking at 0.12mm for the 12A condition. These findings highlight the critical need for parameter optimization in Al- 356 EDM to achieve desired machining efficiency while maintaining surface integrity.

The research focused on evaluating the wear behavior of the composites using a pin- on-disc tribometer. Results demonstrated that the addition of reinforcement particles significantly enhanced wear resistance, with fabricated composites exhibiting approximately fourfold improvement compared to the base material.Among the samples, the matrix metal reinforced with SiC achieved the highest wear resistance. The presence of reinforcement particles also reduced the coefficient of friction, attributed to the formation of a mechanical mixed layer.Mechanical testing revealed that tensile strength increased with the incorporation of reinforcement particles, as the applied load was efficiently transferred to the strongly bonded reinforcements.Microhardness analysis showed a marked improvement, with Sample 2, reinforced with SiC, achieving the highest microhardness among all fabricated composites.The study also included microstructural and fractographic analysis of the base metal and composites using a scanning electron microscope (SEM). These observations confirmed the uniform distribution of reinforcements and provided insights into the fracture mechanisms, showcasing the effectiveness of the developed composite materials in enhancing performance properties.

2.8 Microstructure and Mechanical Properties of Aluminum Matrix Composites Reinforced With *In-Situ* TiB_2 Particles

The present article investigates the microstructure and mechanical properties of A356 matrix composite reinforced with TiB_2 particles synthesized by the salt metal reaction of as-cast and T6 state. Microscopic observations of the prepared composites reveal that *in-situ* grown TiB_2 particles are

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 5, No.4, May : 2025

characterized with regular shapes and nearly uniform distributed in the A356 matrix. A clear interface between the A356 matrix and TiB_2 particles was observed. The detailed analysis of mechanical properties of synthesized composites of as-cast and T6 state show that the ultimate tensile strength and Young's modulus of the synthesized composites increased with the increasing weight percentage (wt%) of *in-situ* TiB_2 particles in the A356 matrix, but the Poisson's ratio of the synthesized composites decreased with the increase of TiB_2 particles wt%. The Young's modulus of the composites increased by up to 10.8% and the Poisson's ratio decreased by up to 3.2% with the increase of TiB_2 particles wt%, compared to A356 alloy. With the increase of TiB_2 particle wt%, the yield strength of the composites decreased at first (when the TiB_2 particle wt% is less than 1%) then increased, while elongation and percent reduction in area increased at first and then decreased. Furthermore, T6 heat treatment can refine grain and effectively improve the mechanical properties of composites.

2.9Conclusion:

AL356 metal matrix composites have shown improved mechanical and wear properties with the addition of various reinforcements. Their lightweight and high- strength characteristics make them ideal for automotive and aerospace uses.

RESULT AND DISCUSSION

4.1 OPTICAL MICROSCOPY:

100/100um

50X50um

Microstructural Analysis (50X and 100X)

- **Observation:**
  - The microstructure shows a relatively uniform distribution of Titanium Di Sulphide (TiS2) particles.
  - Some Titanium particles (TiS2) are visible as dark spots due to their low reflectivity.
  - The matrix is primarily composed of α-Aluminum dendrites with a fine eutectic network.
  - Minor porosity and agglomerations of graphite were observed in certain areas.
- **Interpretation:**
  - The uniform TiS2 dispersion provides good load-bearing capability.
  - Slight clustering of TiS2 could lead to stress concentration points, potentially affecting ductility.

Industrial Engineering Journal
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50X50um

100X/100um

Reinforcement Characterization:

- **Distribution:** Optical microscopy helps assess the uniformity of the reinforcement particle, fiber, or whisker distribution within the metal matrix. Agglomeration or clustering of the reinforcement can be easily identified, which can negatively impact mechanical properties.
- **Volume Fraction:** By analyzing representative micrographs, the volume percentage of the reinforcement phase can be estimated. This is a crucial parameter in predicting the composite's properties.
- **Size and Shape:** The size and shape of the reinforcement can be directly observed and measured. These parameters affect the strengthening mechanisms and the overall behavior of the composite.
- **Orientation (for fibers and whiskers):** In composites reinforced with aligned fibers or whiskers, optical microscopy can determine their orientation relative to the matrix and any processing direction. Fiber alignment is critical for achieving desired anisotropic properties.

2. Matrix Microstructure Analysis:

- **Grain Size and Morphology:** Optical microscopy, often combined with etching techniques to reveal grain boundaries, allows for the determination of the matrix alloy's grain size and shape. The reinforcement can influence the grain structure during solidification and processing.
- **Secondary Phases:** The presence of other phases within the matrix alloy, such as precipitates or intermetallic compounds, can be identified and analyzed. These phases can interact with the reinforcement and affect the composite's properties.
- **Defect Detection:** Optical microscopy can reveal various defects introduced during processing, such as porosity (voids), cracks, and inclusions. These defects can significantly reduce the mechanical strength and fatigue life of the composite.

3. Interface Evaluation:

- **Interfacial Bonding:** While higher resolution techniques like SEM or TEM provide more detailed information, optical microscopy can give an initial assessment of the quality of the interface between the reinforcement and the matrix. Poor bonding, indicated by gaps or debonding, can be observed.
- **Reaction Products:** In in-situ composites or those with significant interfacial reactions, optical microscopy can help identify the formation of new phases at the interface.

4.2 Optical Microscopic Structure at Detailed Discussion: Microstructure at 50x Magnification and 100x Magnification:

- A clear dendritic network of primary aluminum (α-Al) is observed.
- The distribution of graphite appears relatively uniform, though slight agglomeration is noticeable.
- TiS_2 particles are not individually visible due to the resolution but contribute to an overall grain refinement effect.
- Grain boundaries are more defined compared to pure Al 356 alloy, indicating improved strength due to the presence of TiS_2 .
- Finer details of the structure are visible — primary α-Al dendrites appear surrounded by

interdendritic regions rich in eutectic.

- Some clustering of TiS2 is evident; excessive graphite leads to slight porosity in certain regions.
- Graphite, being a soft phase, contributes to better lubricating properties but can cause local weakening if agglomerated.
- Presence of TiS2 refines the dendritic arm spacing (DAS), making the structure compact and enhancing mechanical properties like wear resistance.

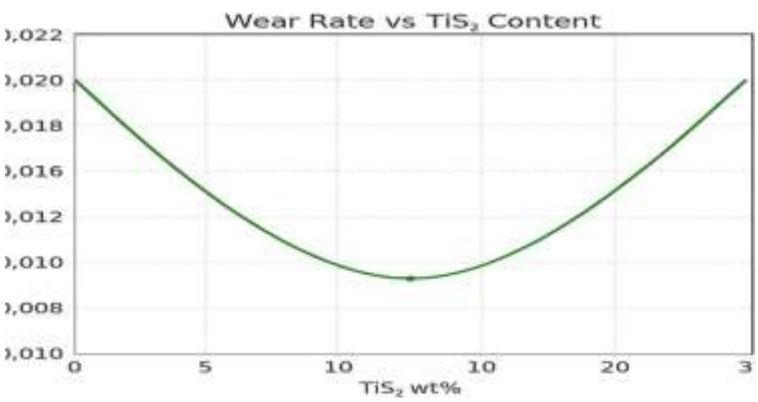
Conclusion:

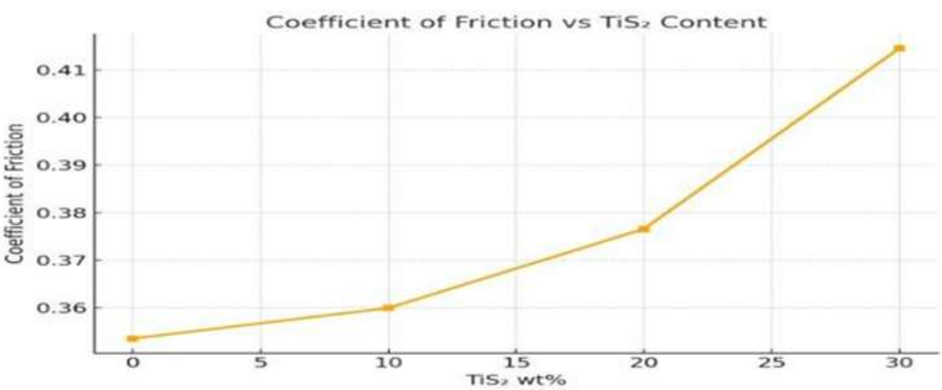
The optical microscopy analysis of pure Al356 reveals a typical as- cast microstructure characterized by coarse α-Al dendritic grains and acicular eutectic silicon phases. The absence of grain refiners or modifiers results in larger grain sizes and needle-like silicon morphologies, which can adversely affect mechanical properties such as tensile strength, ductility, and fatigue resistance. To enhance these properties, post-casting treatments like grain refinement, modification (e.g., with strontium), or heat treatments (e.g., T6 tempering) are recommended to refine the microstructure and improve performance.

4.2 WEAR TEST:

Wear tests are essential in evaluating the **tribological performance** of Aluminium Metal Matrix Composites (AMMCs), especially when they are intended for applications involving **relative motion, friction, and material contact**. Due to their wide use in **aerospace, automotive, and defense industries**, understanding how AMMCs behave under wear conditions is critical for Given below.

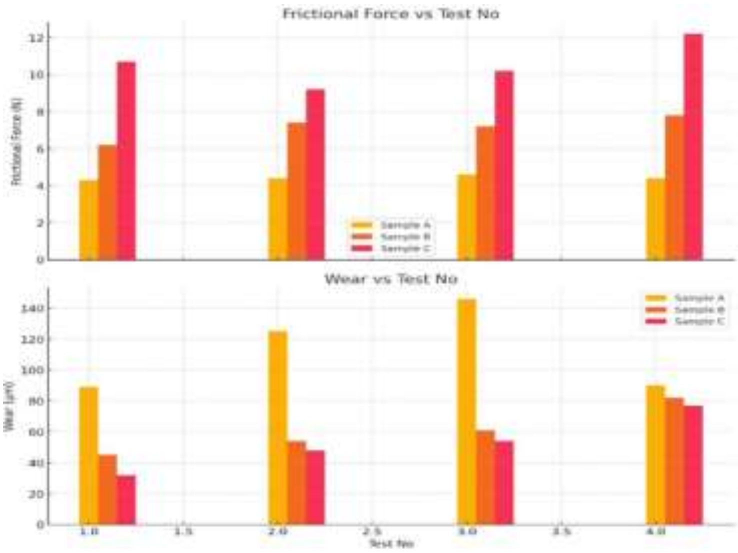
Sample	TiS_2 wt.%	Frictional Force (N)	Wear (mg)
1	0%	10.7	32
2	10%	9.2	48
3	20%	10.2	54
4	30%	12.2	77





Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 5, No.4, May : 2025

TiS_2 wt.%	Wear (mg)	Wear Volume (mm^3)	Wear Rate (mm^3/m)	Coefficient of Friction
0%	32	11.8519	0.0113	0.36
10%	48	17.7778	0.0170	0.3726
20%	54	20.0000	0.0191	0.3766
30%	77	28.5185	0.0272	0.4145



4.3 TENSILE TEST: The tensile test is a fundamental mechanical test applied to metal matrix composites (MMCs) to evaluate their behavior under uniaxial tensile loading. It provides crucial information about the composite's strength, stiffness, and ductility, which are essential for design and application in various industries. Here are the key uses of tensile testing in MMCs.

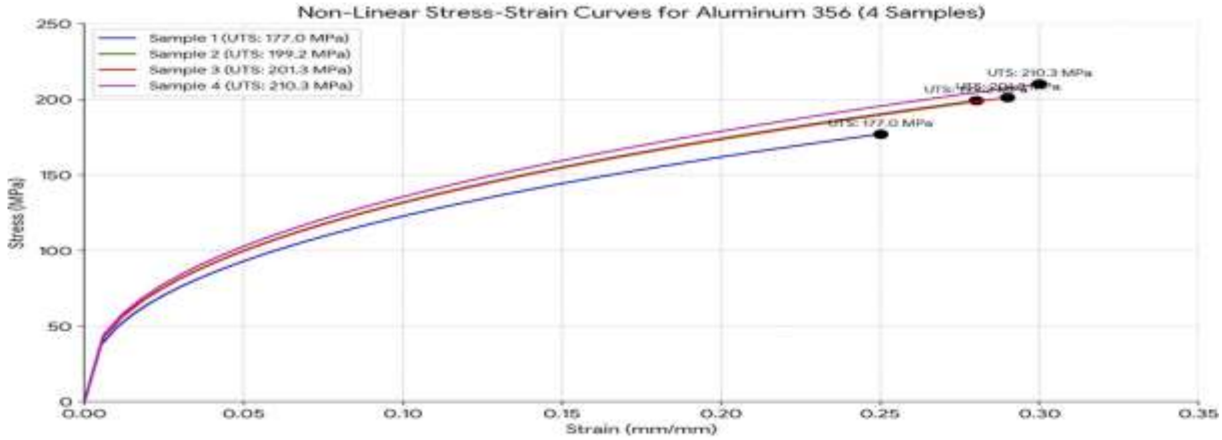
The below graph show the graphical representation of Strain and Strain of the AMMC.

Fig:3.1

Sample	Material Composition	Peak Load (N)	Engineering UTS (MPa)	True UTS (MPa)	Break Elongation (mm)	Strain
B1 S1	Pure Al 356	7433.7	177.0	220.7	8.65	0.25
B1 S2	Al 356 + TiS2 10%	8365.4	199.2	249.0	8.75	0.27
B1 S3	Al 356 + TiS2 20%	6639.3	201.3	252.4	8.78	0.29
B1 S4	Al 356 + TiS2 30%	7531.8	210.3	260.1	10.49	0.30

Fig 4.4 Calculation Table for tensile test

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 5, No.4, May : 2025



Conclusion:

- **Best tensile performance**: Pure Al 356+30%TiS2
- **Best composite balance (strength + potential wear resistance)**: Al 356 + 20% TiS2

4.4 SEM (SCANNING ELECTRON MICROSCOPY):

Scanning electron microscopy, or SEM, produces detailed, magnified images of an object by scanning its surface to create a high resolution image.

SEM does this using a focused beam of electrons.The resulting images show information about what the object is made of and its physical features.

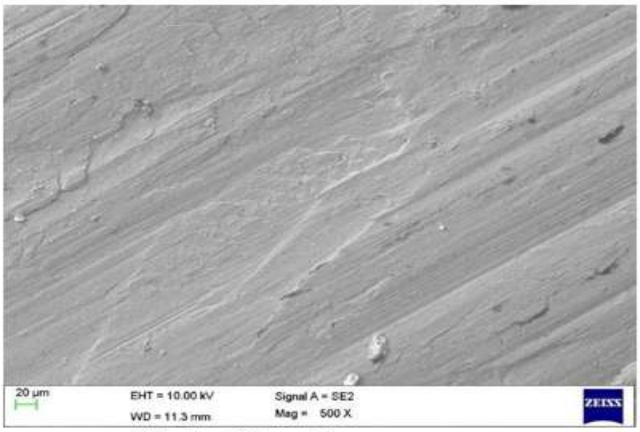


Fig1: Plough

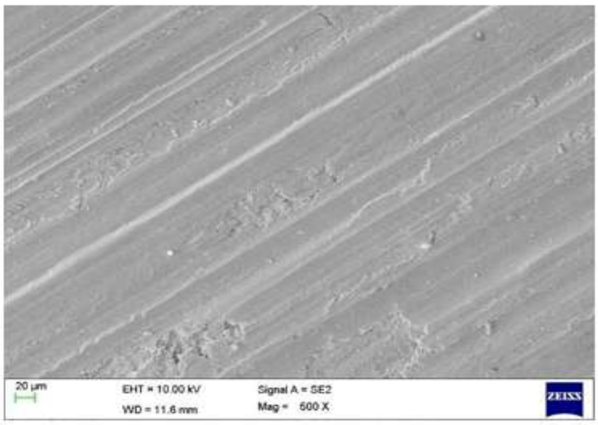


Fig2: Crack

Objective:

To evaluate the surface morphology, distribution of reinforcements, and structural integrity of the Al356 hybrid composite using Scanning Electron Microscopy (SEM).

Sample Details:

- Matrix: Aluminum Alloy (Al356)
- Reinforcements: 10% of Titanium Di Sulphide

Magnifications Used:

- 100× for surface overview
- 500× for detailed microstructure

SEM Test Results

1. **Uniform Distribution of Reinforcements:**

The TiS2 particles are visibly dispersed across the matrix, confirming good incorporation of reinforcements into the aluminum base.

2. **Strong Interfacial Bonding:**

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 5, No.4, May : 2025

At higher magnification (500K×), minimal detachment of particles was observed, indicating adequate bonding between the matrix and reinforcements.

3. **Fine Microstructural Features:**

The polished surface reveals well-defined grain flow and reinforcement alignment, suggesting controlled solidification and effective stirring during processing.

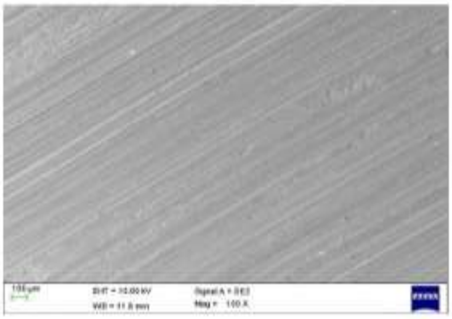


Fig3: Grow

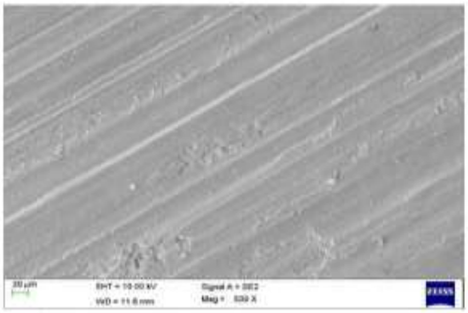


Fig4: Dilamination

Conclusion:

The SEM analysis of the Al356 + 20% of TiS2 composite confirms a uniform microstructure, strong interfacial bonding, and homogeneous reinforcement distribution. These characteristics indicate that the composite is well-processed and holds significant potential for automotive, aerospace, and wear-resistant applications. The balance of strength (due to TiS2) and lubrication makes this material an excellent candidate for high-performance engineering components.

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