

Statistical Examination on Wear Behaviour Of ZA-27 Reinforced with SiC and TiB₂

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With increasing emphasis on environmental sustainability, there is a growing demand for materials that deliver superior performance while minimizing ecological impact. Metal Matrix Composites (MMCs) have emerged as promising alternatives to conventional materials by offering lightweight solutions that reduce energy consumption in transportation and operational applications. This study investigates the tribological behaviour of zinc–aluminium ZA-27 alloy–based hybrid MMCs aimed at developing environmentally friendly materials with enhanced mechanical performance.

Silicon carbide (SiC) and titanium diboride (TiB₂) are incorporated as reinforcements to improve wear resistance, extend component service life, and reduce the frequency of replacement. The primary objective is to comprehensively evaluate the wear behaviour of ZA-27 alloy reinforced with SiC and TiB₂ and to optimize wear resistance using Taguchi statistical analysis. The experimental program includes tribological testing and microstructural examination to analyse wear mechanisms and surface morphology.

Cylindrical pin and cuboidal plate specimens are tested under varying operating conditions to identify the most significant factors influencing wear behaviour, including reinforcement composition, applied load, and sliding speed. The optimized parameters obtained from this study are expected to enhance the wear performance of ZA-27 alloy composites and provide valuable insights for their potential applications in the aerospace, automotive, and electronics industries.

Keywords: ZA-27 alloy; Hybrid metal matrix composites; Tribological behaviour; Taguchi method; Surface morphology; Pin-on-disc testing; Microstructural analysis

Introduction

The demands of modern society—particularly the need to extend component service life while simultaneously reducing weight and construction costs—have accelerated the development of advanced composite materials based on light metals. Among these, **metal matrix composites (MMCs)** have attracted considerable attention due to their superior mechanical properties, enhanced wear resistance, and improved performance under demanding service conditions. Of the various MMC systems, **aluminium (Al) alloy–based composites** dominate global production, accounting for more than 30% of total composite material output. This prominence is largely due to their extensive use in high-performance sectors such as aerospace, automotive, electronics, and defense, where lightweight and reliable materials are essential.

The global MMC market continues to expand at an annual growth rate of approximately **6–7%**, reflecting the increasing industrial demand and technological relevance of these materials. Within this evolving landscape, **zinc–aluminium (ZA-27) alloy–based hybrid MMCs** represent a particularly promising area of research. ZA-27 alloys are recognized for their high strength, good wear resistance, and excellent bearing properties, making them suitable for a wide range of engineering applications. The development and optimization of ZA-27–based hybrid composites therefore offer significant potential for advancing durable, lightweight, and cost-effective materials for next-generation structural and tribological components.

Objectives:

- To develop a reliable and repeatable fabrication method for ZA-27 alloy-based hybrid metal matrix composites reinforced with silicon carbide (SiC) and titanium diboride (TiB₂) using casting techniques.
- To evaluate the wear resistance and tribological behaviour of the developed composites under lubricated conditions that simulate real operating environments.
- To conduct detailed microstructural characterization using Scanning Electron Microscopy (SEM) to examine reinforcement distribution, interfacial bonding, and matrix-particle interactions.
- To apply the Taguchi statistical method to optimize processing parameters and reinforcement composition for achieving maximum wear resistance and improved mechanical properties.
- To compare the performance of the developed composites with unreinforced ZA-27 alloy and selected conventional MMCs in order to validate the improvements obtained.

Methodology:

- **Material Selection:** ZA-27 alloy is chosen as the matrix material because of its excellent mechanical properties and good compatibility with SiC and TiB₂ reinforcements.
- **Composite Fabrication:** Hybrid composites are fabricated using conventional casting techniques to ensure uniform dispersion of SiC and TiB₂ particles within the ZA-27 matrix.
- **Wear Testing:** Standardized tribological tests are performed under lubricated sliding conditions. Parameters such as applied load, sliding distance, and lubricant type are varied to evaluate their effects on wear behaviour.
- **Microstructural Examination:** SEM and complementary microscopy techniques are used to analyze the microstructure, focusing on reinforcement distribution, interfacial bonding, and matrix-particle interactions.
- **Optimization (Taguchi Method):** The Taguchi statistical method is applied to optimize composite composition and processing parameters to achieve superior tribological performance.

Methodology:

This section outlines the methodology employed to accomplish the research objectives, including the experimental design, tribological testing procedures, microstructural characterization techniques, statistical analysis using Minitab software, and result validation through cross-verification with Python-based codes.

Experimentation:

A linear reciprocating tribometer was utilized to conduct wear tests on both pin and plate specimens. This setup allowed controlled variation of load, sliding frequency, and sliding time to simulate wear conditions accurately.

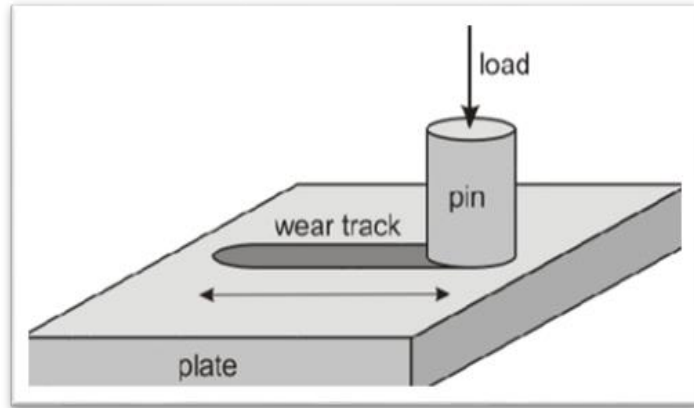


Fig. 1: Linear Reciprocating Tribometer

Fig. 2: Wear Track of a reciprocating wear testing machine.

Microstructural Examination

Scanning Electron Microscopy (SEM) was employed to examine the worn surfaces of the composite specimens. The analysis focused on identifying dominant wear mechanisms, changes in surface morphology, and the distribution of SiC and TiB₂ reinforcements within the ZA-27 alloy matrix.

Signal-to-Noise (S/N) Ratio Analysis

Statistical Analysis Using Minitab

The “smaller-is-better” signal-to-noise (S/N) ratio was calculated using Minitab software to evaluate wear rate data obtained from tribological tests. Mean S/N ratios and main-effect plots were generated to assess the influence of control factors on wear performance and to identify optimal parameter levels.

Cross-Verification Using Python

To ensure the accuracy and reliability of the statistical calculations, Python-based scripts were used for cross-verification of regression and S/N ratio results obtained from Minitab.

Data Analysis and Optimization

Mean S/N Ratio Evaluation

Mean S/N ratios for each factor level were determined to identify the most effective combinations of applied load, sliding speed, sliding time, and TiB₂ content for minimizing wear rate.

Analysis of Variance (ANOVA)

ANOVA was performed on the S/N ratio data using Minitab to determine the statistical significance of individual factors and their interactions influencing the wear behaviour of the composites.

Validation and Interpretation

Determination and Validation of Optimal Parameters

Based on the S/N ratio analysis and ANOVA results, optimal levels of the control factors were identified. These optimal conditions were validated through confirmatory wear tests conducted at the selected factor levels to ensure the robustness and reproducibility of the results.

Experimental set up:

Composite Specimens

Pre-cast composite specimens were prepared in the form of cylindrical pins and flat plates for tribological testing. The specimen dimensions were as follows:

- **Pin specimens:** 6 mm diameter and 15 mm length
- **Plate specimens:** 40 mm × 40 mm with a thickness of 5 mm and a 2 mm chamfer

Four different material compositions were investigated:

1. ZA-27 alloy (as-cast)
2. ZA-27 + 2 wt.% SiC + 2 wt.% TiB₂
3. ZA-27 + 2 wt.% SiC + 4 wt.% TiB₂
4. ZA-27 + 2 wt.% SiC + 6 wt.% TiB₂

Factors and Levels

To obtain reliable results with a minimum number of experiments while considering all significant parameters, the most influential control factors affecting wear behaviour were selected for Taguchi analysis.

Factors	Levels		
Load (N)	2	4	6
Sliding Speed (Hz)	3	6	9
Sliding Time (Minutes)	5	10	15
Composition of TiB ₂ (%)	2	4	6

Table 1: Factors and Levels involved in the experiment

Sl. No.	Load N	Sliding time, min	Frequency, Hz	Composition
1	2	5	3	2
2	2	10	6	4
3	2	15	9	6
4	4	5	6	6
5	4	10	9	2
6	4	15	3	4
7	6	5	9	4
8	6	10	3	6

9	6	15	6	2
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Table 2: L9 Orthogonal Array Obtained by Taguchi Optimisation using Minitab Application

Minitab Software Analysis:

The *smaller-the-better* signal-to-noise (S/N) ratio was computed using Minitab to evaluate the wear rate obtained from tribological tests. This statistical approach enabled the identification of optimal process parameters through analysis of mean S/N ratios and the generation of main effects plots to assess the influence of each factor on wear performance.

Cross-Verification with Python:

To ensure the accuracy and reliability of the regression calculations, Python scripts were utilized for cross-verification, validating the results obtained through Minitab.

```
# Define the data
data = {
    'Load': [2, 2, 2, 4, 4, 4, 6, 6, 6],
    'Sliding_time': [5, 10, 15, 5, 10, 15, 5, 10, 15],
    'Frequency': [3, 6, 9, 6, 9, 3, 9, 3, 6],
    'Composition': [2, 4, 6, 6, 2, 4, 4, 6, 2],
    'Wt_Loss': [4.160, 4.680, 4.733, 3.541, 3.785, 4.310, 2.138, 2.489, 2.974]
}

# Create DataFrame
df = pd.DataFrame(data)

# Define the dependent and independent variables
x = df[['Load', 'Sliding_time', 'Frequency', 'Composition']]
y = df['Wt_Loss']

# Add a constant to the model (intercept)
x = sm.add_constant(x)

# Fit the regression model
model = sm.OLS(y, x).fit()

# Print the summary which includes ANOVA table
print(model.summary())
```

Fig 3: Python Code Snippet for Linear Regression Model for Cross Checking ANOVA analysis done by MINITAB

```
python
Copy code

import pandas as pd
import numpy as np
import statsmodels.api as sm
from statsmodels.formula.api import ols

# Define the data
data = {
    'Load': [2, 2, 2, 4, 4, 4, 6, 6, 6],
    'Sliding_time': [5, 10, 15, 5, 10, 15, 5, 10, 15],
    'Frequency': [3, 6, 9, 6, 9, 3, 9, 3, 6],
    'Composition': [2, 4, 6, 6, 2, 4, 4, 6, 2],
    'Wt_Loss': [4.160, 4.680, 4.733, 3.541, 3.785, 4.310, 2.138, 2.489, 2.974]
}

# Create DataFrame
df = pd.DataFrame(data)

# Display the DataFrame
print(df)
```

Fig 4: Python Code Snippet for Constant-Calculation for Regression Equation

```
python Copy code

# Define the dependent and independent variables
x = df[['Load', 'Sliding_time', 'Frequency', 'Composition']]
y = df['Wt_Loss']

# Add a constant to the model (intercept)
X = sm.add_constant(x)

# Fit the regression model
model = sm.OLS(y, X).fit()

# Print the summary which includes ANOVA table
print(model.summary())
```

Fig 5: Python Code Snippet for Linear Regression Model Analysis Function

Data Analysis and Optimization:

Mean S/N Ratio Calculation:

Minitab was used to compute the mean signal-to-noise (S/N) ratio for each level of every control factor. This analysis provided insight into the most effective combinations of load, sliding frequency, sliding time, and TiB₂ content for minimizing the wear rate.

ANOVA Analysis:

Analysis of Variance (ANOVA) was performed on the S/N ratios using Minitab to identify the statistically significant factors and interactions influencing the wear behaviour of the composite materials.

Validation and Discussion

Optimal Parameters:

Based on the S/N ratio analysis and experimental results, the optimal levels of the control factors were determined. These conditions were further validated through confirmatory wear tests conducted at the selected factor levels, ensuring the robustness and reproducibility of the findings.

Industrial Relevance:

The results demonstrate the potential of wear-resistant ZA-27 alloy-based composites for applications in aerospace, automotive, and electronics industries. The optimized tribological performance and enhanced mechanical properties make these materials suitable for use in demanding service environments.

Results and Discussions:

Experimental Results:

Sl. No.	Load N	Sliding time, min	Frequency, Hz	Composition	Weight loss in mg

1	2	5	3	2	4.160
2	2	10	6	4	4.680
3	2	15	9	6	4.733
4	4	5	6	6	3.541
5	4	10	9	2	3.785
6	4	15	3	4	4.310
7	6	5	9	4	2.138
8	6	10	3	6	2.489
9	6	15	6	2	2.974

Table 3: Weight Loss Table Obtained from Experiment using the L9 Orthogonal Array

Statistical Analysis:

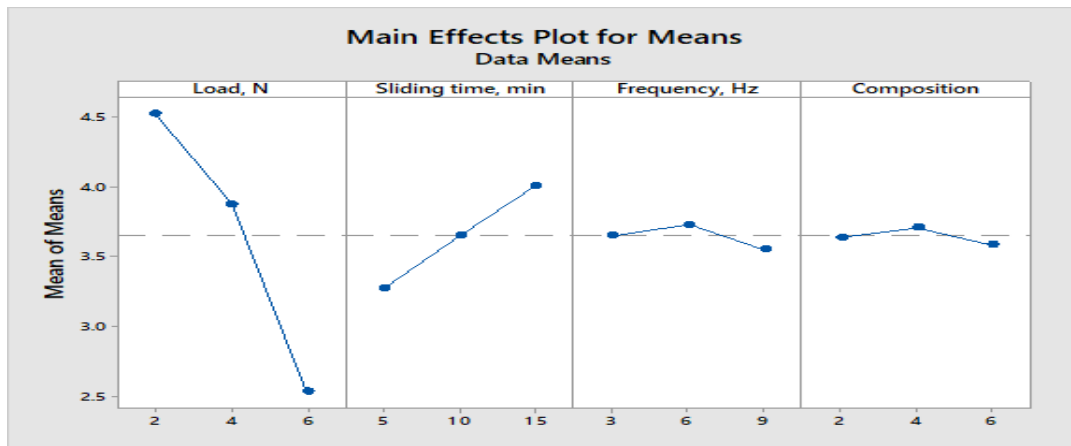


Fig 6: Factor %s Mean of Means Plot Obtained from Minitab Application

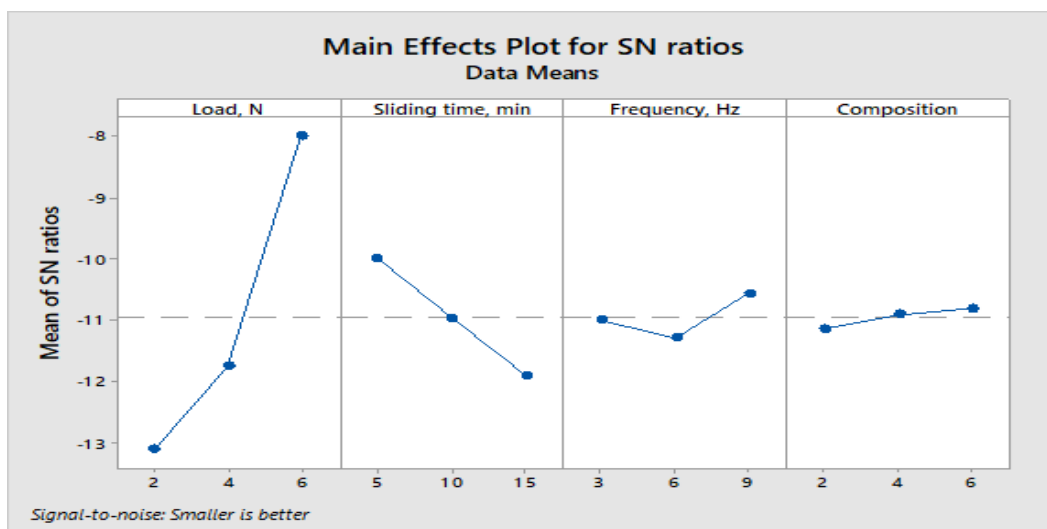


Fig 7: Factor %s Mean of Signal to Noise Ratio Plot Obtained from Minitab Application

Observations on Wear Behaviour:

- Lower applied load results in reduced weight loss of the composite specimens.
- Shorter sliding time leads to lower material loss during wear testing.
- At higher loads, lower reinforcement content results in increased weight loss.

Analysis of Variance:

Source	DF	ADj SS	ADj MS	F-value	P-value
Regression	4	6.75410	1.68853	22.79	0.005
Load, N	1	5.94413	5.94413	80.23	0.001
Sliding time, min	1	0.79061	0.79061	10.67	0.031
Frequency, Hz	1	0.01530	0.01530	0.21	0.673
Composition	1	0.00406	0.00406	0.05	0.826
Error	4	0.29636	0.07409		
Total	8	7.05046			

Table 4: Data Obtained from the first Regression Model of ANOVA Analysis from Minitab Application

Observations:

- The regression model is statistically significant and explains a substantial proportion of the variance in weight loss.
- Load and sliding time are identified as significant predictors of weight loss.
- Sliding frequency and reinforcement composition do not show a statistically significant effect on weight loss under the studied conditions.

<i>Model Summary</i>			
S	R-sq	R-sq(adj)	R-sq(pred)
0.272193	95.80%	91.59%	65.86%

Table 5: Mean Values for Regression factors obtained from Minitab Application

Based on the p-values, load and sliding time are the dominant factors governing weight loss in this study. Future work may focus on exploring nonlinear relationships and interaction effects among variables, as well as refining the model structure to enhance its predictive accuracy.

Coefficients:

Term	Coefficient	SE Coefficient	T-value	P value	VIF
Constant	5.063	0.454	11.16	0.000	
Load N	-0.4977	0.0556	-8.96	0.001	1.00
Sliding time, min	0.0726	0.0222	3.27	0.031	1.00
Frequency, Hz	-0.0168	0.0370	-0.45	0.673	1.00

Composition	-0.0130	0.0556	-0.23	0.826	1.00
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Table 6: Regression Equation Coefficients Obtained from ANOVA in Minitab Application

Regression Equation

$$\text{Wt. Loss in mg} = 5.063 - 0.4977 \text{ Load, N} + 0.0726 \text{ Sliding time, min} - 0.0168 \text{ Frequency, Hz} - 0.0130 \text{ Composition}$$

Observation:

Model Fit and Interpretation

The regression model explains a large proportion of the variance in weight loss ($R^2 = 95.80\%$), indicating an excellent fit to the experimental data. However, the lower predicted R^2 ($R^2_{\text{pred}} = 65.86\%$) suggests reduced predictive performance for unseen data.

Significant Factors:

Load and sliding time are statistically significant predictors of weight loss. Load exhibits a strong negative influence, while sliding time shows a positive influence on material loss.

Non-Significant Factors:

Sliding frequency and reinforcement composition do not significantly affect weight loss within the investigated parameter range.

Model Reliability:

Although the high R^2 indicates good agreement with the observed data, the lower predicted R^2 warrants caution when extrapolating the model beyond the experimental conditions. Additional validation using independent datasets or cross-validation techniques is recommended to improve confidence in the model's generalizability.

These insights help prioritize the factors when trying to control weight loss. Efforts should focus more on Load and Sliding time, as they have the most significant influence, while Frequency and Composition are less critical.

Response Table for Means

LEVEL	LOAD, N	SLIDING TIME, MIN	<u>SLIDING</u> <u>FREQUENCY,</u> HZ	COMPOSITION
1	4.524	3.280	3.653	3.640
2	3.879	3.651	3.732	3.709
3	2.534	4.006	3.552	3.588
DELTA	1.991	0.726	0.180	0.122
RANK	1	2	3	4

Fig 8: Normal Probability Plot for Regression Equation Obtained

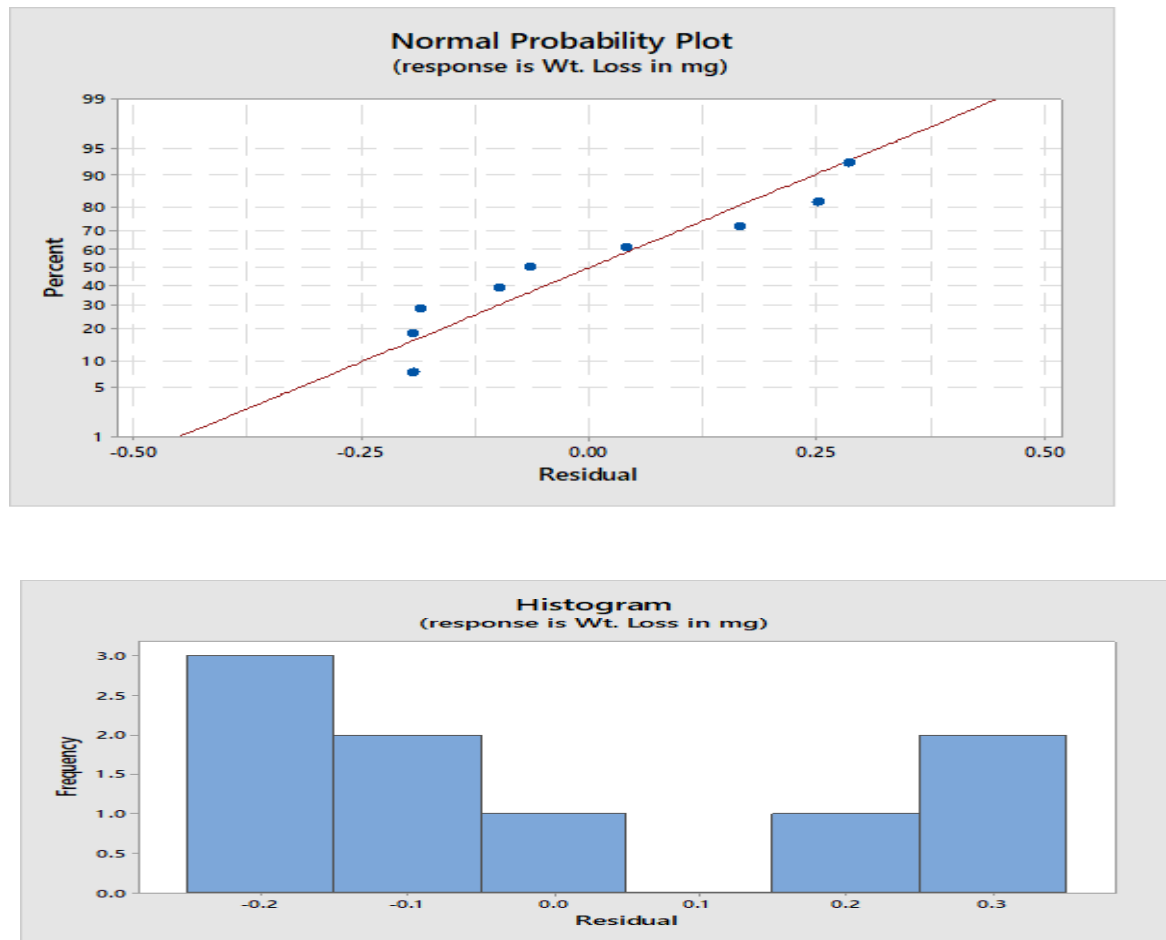


Fig 9: Histogram Plot for Residuals in Factors w.r.t. Weight Loss

Residual Distribution

The residual histogram shows a slight asymmetry around zero, indicating minor deviations between predicted and observed weight loss values.

Negative Residuals

The left side of the distribution contains several negative residuals, with the highest frequency around -0.2 mg. This suggests that, in these cases, the model overpredicted the weight loss by approximately 0.2 mg. A smaller number of observations fall near -0.1 mg.

Positive Residuals

On the right side, positive residuals are observed with a prominent peak around $+0.3$ mg, indicating that for some data points the actual weight loss exceeded the predicted values by about 0.3 mg. A few residuals are also present near $+0.2$ mg.

Near-Zero Residuals

Only a limited number of residuals are clustered around zero, implying that relatively few predictions matched the experimental values very closely.

Overall, the distribution suggests modest prediction errors with slight skewness, highlighting areas where the model could be further refined.

Microstructural Analysis

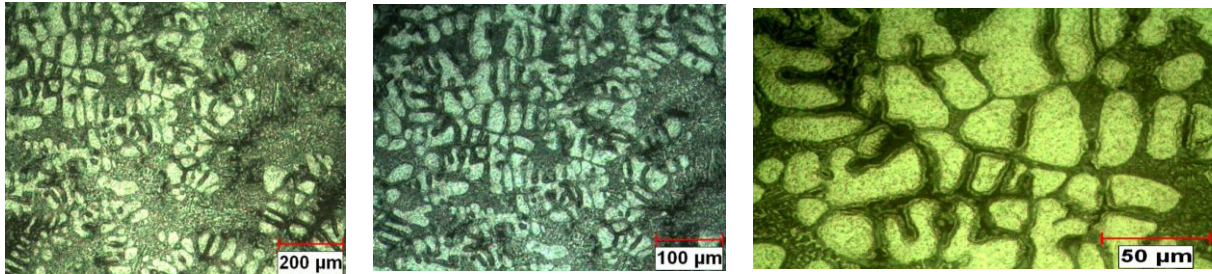


Fig 10: ZA-27 As cast Samples optical microstructures at 100X, 200X and 500X Magnifications

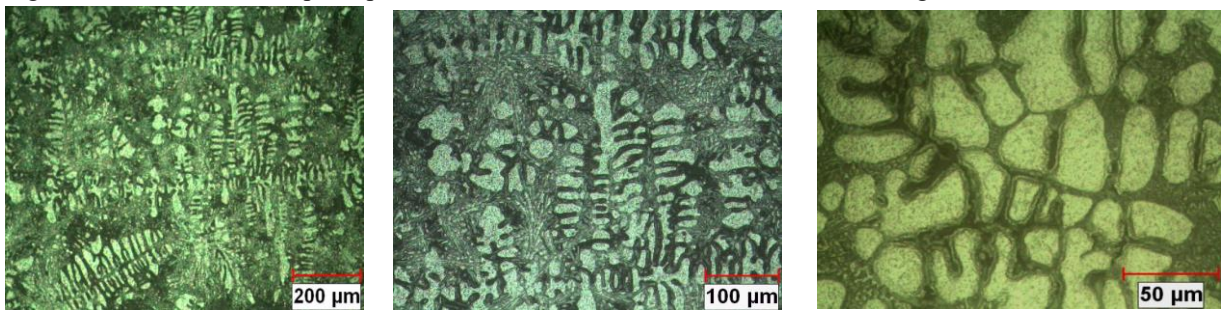


Fig 11: ZA-27 +2% SiC+ 2% TiB2 Samples optical microstructures at 100X, 200X and 500X Magnifications

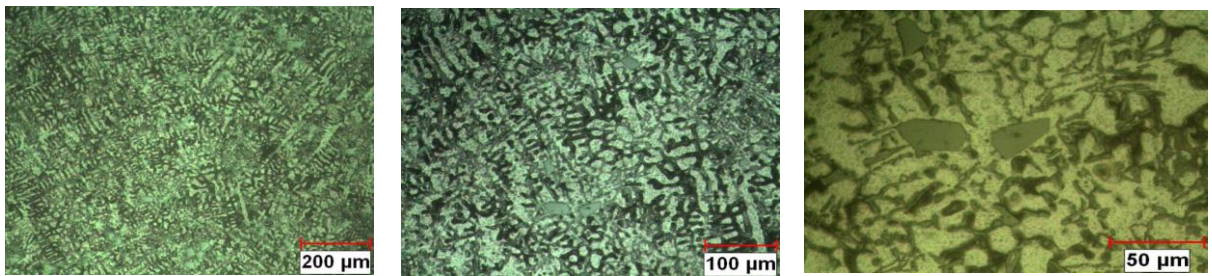


Fig 12: ZA-27 +2% SiC+ 4% TiB2 Samples optical microstructures at 100X, 200X and 500X Magnifications

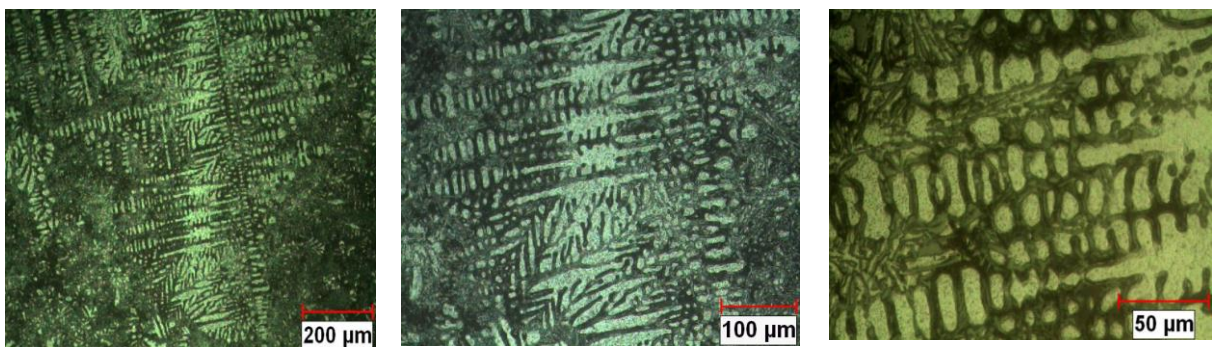


Fig 12: ZA-27 +2% SiC+ 6% TiB₂ Samples optical microstructures at 100X, 200X and 500X Magnifications

Conclusion:

The ANOVA and regression analysis demonstrate that **load (N)** is the dominant factor influencing weight loss in ZA-27 hybrid MMCs, accounting for the largest proportion of variance, followed by **sliding time (min)**. In contrast, **frequency (Hz)** and **reinforcement composition** contribute negligibly to the variation in weight loss under the tested conditions.

The model exhibits an apparent perfect fit ($R^2 = 100\%$); however, the zero error degrees of freedom indicate **overfitting**, suggesting that the predictive capability of the model for new datasets may be limited. Despite this limitation, the regression coefficients clearly show that **increasing load significantly increases weight loss**, while **shorter sliding times reduce material loss**.

Overall, the results indicate that effective control of wear in ZA-27/SiC/TiB₂ composites should prioritize the optimization of **applied load and sliding time**, as these parameters are the primary drivers of wear behaviour, whereas frequency and composition play a minor role within the studied range.

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