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# Analysis of Wear Parameters of Chill Casted LM13/Zircon/Carbon Hybrid Composites Using Experimental and Statistical Approach

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**Abstract:** In this article Effect of wear parameters like load, sliding speed, and sliding distance are analyzed on wear rate. The influence of the weight percentage of zircon on wear rate is studied. The wear rate analysis is done using the Analysis of variance technique (ANOVA) and SN curve with the help of MINITAB software. Specimens are prepared at the ratio of (0+3), (3+3), (3+6), (3+9) and (3+12) weight percentages of Carbon and zircon are added to Aluminum alloy (LM13) respectively. Synthesis is done using a stir casting approach and Copper chill is placed at one end of the mold before pouring the molten composite. Copper chill is placed to have unidirectional solidification and wear properties are evaluated at the chill end of the solidified composite. In the Dry Sliding Pin on Disc wear experimental, it was observed that 9wt.% of zircon shows better wear resistance than other combinations of carbon and zircon combination reinforcement. It is also seen that the wear rate increases as load, sliding speed, and sliding distance increase. The effect of wear parameters is studied and the most influencing wear parameter is analyzed. Results showed that the weight percentage of zircon exerted the greatest effect on wear rate. The wear surface morphology of the specimens is examined. Wear debris, Grooves, and delamination are observed at low Wt.% of reinforcements.

Keywords: analysis of variance technique, dry sliding pin on disc, surface morphology, wear debris, wear

## Introduction

Composites play a vital role in the selection of materials for desired applications [1], reinforcement is a crucial section in selecting a material for a composite which should provide better strength to the composite [2], Dual particle reinforcement (DRP) gives better wear results when compared to single particle reinforcement [3], It pertains high resistance to wear than a single reinforced composite [4], ceramic reinforcement is preferred as the reinforcement for structural and wear resistant applications [5]. The addition of graphite to the composite decreases the wear rate and a uniform graphite layer on the worn surface is observed in microstructural studies. Stir casting process is used synthesis of metal matrix composite for its even mixture of matrix and reinforcement [6],chill casting is a special type of casting technique which provide unidirectional solidification for the liquid composite in a mould [7], Taguchi method is used to decrease the number of experiments and decides the optimum value by using L9 orthogonal vector for wear testing condition variables[8], addition of graphite flakes to the matrix erodes the matrix material and leads to the formation of graphite holes which intern move along counterpart movement during wear[9], wear is a function of load, temperature and wt.% of reinforcement[10], SiC and $ZrSiO_4$ combination of reinforcements contributes to decrease in wear and can be applied to marine industry and marine environment[11], During initial less speed of the pin , wear is abrasive and continues to be delaminating at higher speeds[12],Thick and stable tribo layers are formed on the Graphite aluminum composite and its hardness increases for higher loads and speed [13]. Grain size affects the strength and wear properties of the composite structure, finer the grains better the properties [14], Empirical relation is established to study wear rate using statistical regression analysis and analysis of variance (ANOVA)[15], Analysis of variance (ANOVA) technique is a statistical approach used to access the most influencing parameters in the wear study [16].

## 1. Materials and experimental procedures

### 1.1 Materials description and composition

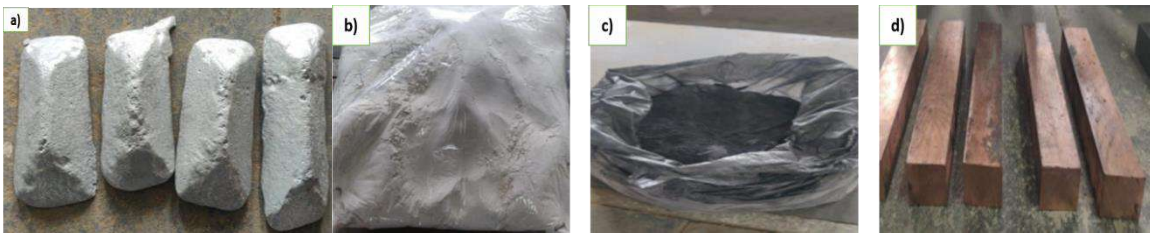
LM13, a light metal alloy is used as a metal matrix, Ceramic $ZrSiO_4$ and carbon in the form of graphite powder are used as reinforcements to the composite preparation. LM13 is selected because of its cast ability and ductile nature with 13Wt% of silicon. $ZrSiO_4$ of 1Micron is selected because of its high compressive strength. Graphite is used to study the improvisation of the properties of LM13. Copper chills are used for unidirectional solidification. The chemical composition of LM13 is shown in the table 1.

**Table 1.** Chemical composition of LM13

| Elements | Zn | Mn | Si | Ni | Fe | Mn | Al |
|---|---|---|---|---|---|---|---|
| Wt.% | 0.5 | 1.0 | 12 | 2.0 | 0.5 | 1.0 | Bal |

**Table 2.** Composition of zircon

| Element | Wt.% |
|---|---|
| Zirconium dioxide ($ZrO_2$) | 64.80 |
| Silicon dioxide ($SiO_2$) | 32.50 |
| Ferric oxide($Fe_2O_2$) | 0.70 |
| Titanium dioxide ($TiO_2$) | 0.15 |
| Alumina ($Al_2O_3$) | 1.20 |




a) aluminum alloy; b) zircon; c) carbon;d) copper chills

**Fig. 1.** - Components

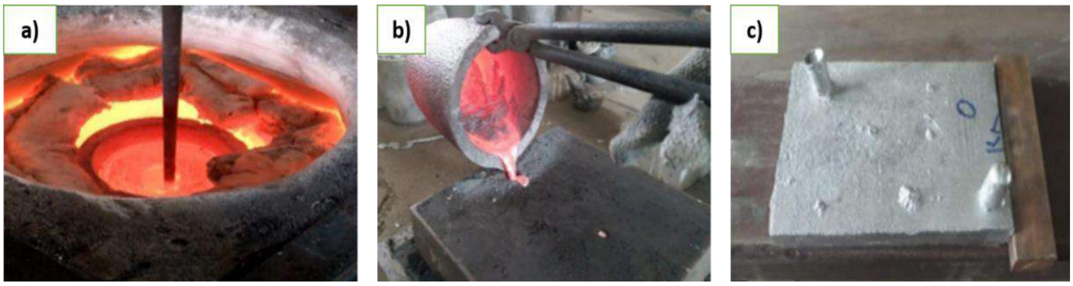
**1.2 Fabrication of the composite**

Specimens are fabricated using the stir-casting process to achieve a homogenous mixture. Reinforcements are preheated at 200 degrees Celsius for 10 minutes to remove the humidity content and avoid agglomerations in the liquid composite. LM13 aluminum alloy is melted to its melting point of 660 degrees Celsius in a graphite crucible and preheated reinforcements are added at the combinations as shown in table 2. Carbon percentage is maintained constant I,e 3wt.% throughout the sets of the experiment. Carbon provides the lubrication property to composite which resists wear. Judiciously 3wt.% is maintained because it withholds the tribo-layer formation [17]. A cast specimen is fabricated initially to find the strength of the material without adding Zircon reinforcement. In casting copper chill is placed at one end of the mold. Copper chill placed at one end provides unidirectional solidification. Hence this paper explains the influence of copper chill and Zircon percentage on the composite.

**Table 3.** Specimen with reinforcement combination

| Specimen Number | Zircon (Wt.%) | Carbon (Wt.%) |
|---|---|---|
| 1 (As cast) | 0 | 3 |
| 2 | 3 | 3 |
| 3 | 6 | 3 |
| 4 | 9 | 3 |
| 5 | 12 | 3 |

**Fig.2.** - Placement of chills to the molds




a) stir casting; b) molten composite pouring to mold; c) composite part

**Fig. 3** - Casting experiment

### 1.3 Wear experiments

The chill end of the specimens is on disc wear test is done for the samples. Test samples of 8mm diameter and 25mm length dimension are cleaned and polished by different grit sizes of emery paper. The test steel disc surface is cleaned with acetone. The specimen is pressed against the steel disc using an attachment which is supported by an arm and lever with an incremental loaded weight. Specimens are weighed before the testing and after the testing to calculate the volumetric loss which results in loss of density of specimen due to wear.

### 1.4 Wear rate

Wear rate is the function of change in weight $(\Delta W)$ of the specimen before and after load, density$(\rho)$, load $(F)$, and sliding distance $(S)$. The relation is given by equation (1):

$$Wear\ Rate = \Delta \frac{W}{\rho FS} \tag{1}$$

Specific wear rate can be calculated by using the relation as shown in equation (2):

$$Specific\ wear\ rate\ (SWR) = \frac{M}{SL} \tag{2}$$

Wear resistance (WR) of a material is that the material offers resistance to the wear can be calculated as shown in equation (3):

$$WR = 1/Wear\ rate \tag{3}$$

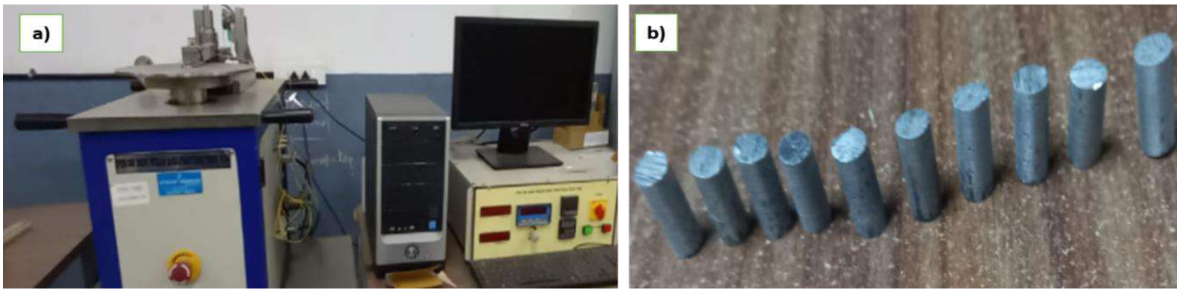
where M is the Average pin weight loss, S is the total sliding distance and L is the load applied in Newton.

### 1.5 Co-efficient of friction

It is the ratio of frictional force (F) resisting the motion to the Normal force (N) as shown in the equation:

$$\mu = F/N \tag{4}$$

Hence coefficient of friction increases as the load/Normal force acting on a pin decreases and vice-versa.




a) dry sliding wear apparatus set up; b) composite pins for experimentation

**Fig. 4**. - Friction experiment

Specimens are tested for wear in different conditions. All specimens indicated in Table 4 undergo a wear test for the conditions shown in Table 4.

**Table 4.** Conditions applied for the specimens for dry sliding wear test

| Exp No | Condition | Applied load (N) | Sliding speed (rpm) | Sliding distance( Track radius in mm) | Exp No | Condition | Applied load (N) | Sliding speed (rpm) | Sliding distance (Track radius in mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Change in Load | 30 | 400 | 30 | 8 | Change in Speed | 30 | 700 | 30 |
| 2 | | 40 | 400 | 30 | 9 | | 30 | 800 | 30 |
| 3 | | 50 | 400 | 30 | 10 | Change in Sliding distance | 30 | 400 | 40 |
| 4 | | 60 | 400 | 30 | 11 | | 30 | 400 | 50 |
| 5 | | 70 | 400 | 30 | 12 | | 30 | 400 | 60 |
| 6 | Change in Speed | 30 | 500 | 30 | 13 | | 30 | 400 | 70 |
| 7 | | 30 | 600 | 30 | | | | | |

## 2 Experimental results

### 2.1 Effect of Applied Load and Zircon % on Wear Rate and Co-Efficient of Friction

2.1.1 Wear rate discussion

As the load on the pin increases incrementally from 30 N to 70N with an increment of 10N by keeping sliding speed and sliding distance parameters constant, the wear rate gradually decreases. Also when the percentage of zircon increases gradually from 3wt.% to 12wt.% with an increment of 3wt.%, the wear rate decreases till 9wt.% of zircon and then it slightly increases as shown in Figure 5 and Table 5. Hence at 30N wear rate is the minimum and at 70N wear rate is the maximum. Also at 3wt.% of zircon wear rate is maximum and at 9wt.% wear rate is minimum.

**Table 5.** Effect of Load applied on wear loss, COF, and wear rate for copper chill end

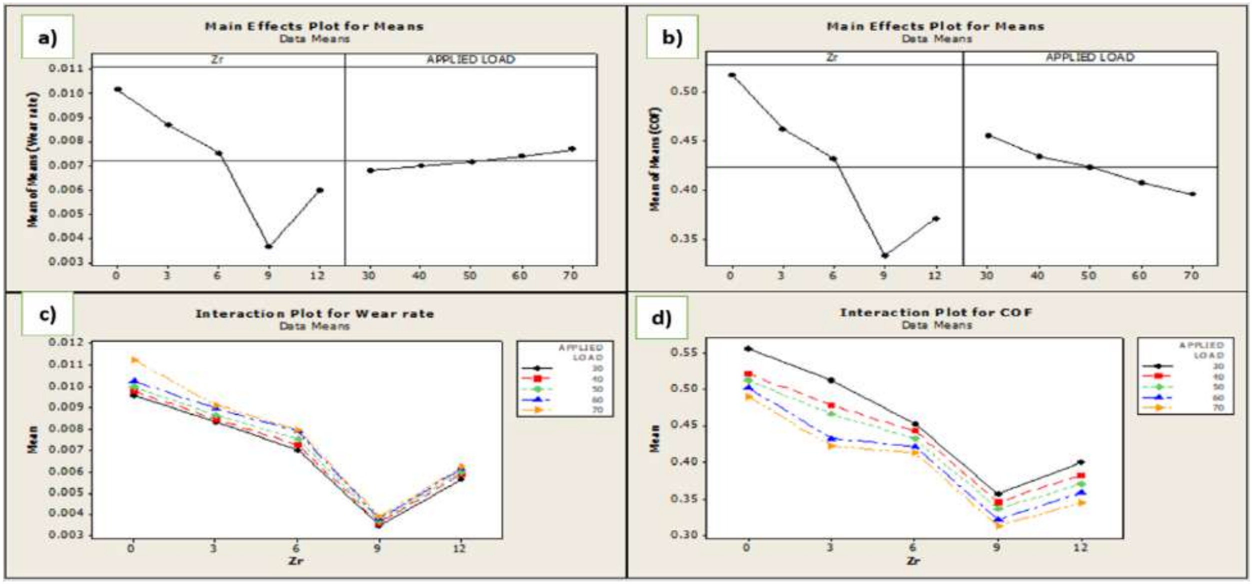
| | AL | RPM | TR | WL | WL SN | COF | COF SN | WR | WR SN |
|---|---|---|---|---|---|---|---|---|---|
| 12 % chill | 30 | 400 | 30 | 0.0078 | 36.8328 | 0.4001 | 0.55513 | 0.0056 | 40.381 |
| | 40 | 400 | 30 | 0.0081 | 36.1375 | 0.3822 | 0.52140 | 0.0058 | 40.184 |
| | 50 | 400 | 30 | 0.0092 | 35.5978 | 0.3700 | 0.51250 | 0.0059 | 40.026 |
| | 60 | 400 | 30 | 0.0105 | 34.8945 | 0.3586 | 0.50210 | 0.0061 | 39.785 |
| | 70 | 400 | 30 | 0.011 | 34.3793 | 0.3447 | 0.48960 | 0.0062 | 38.992 |
| 9% chill | 30 | 400 | 30 | 0.0062 | 39.3315 | 0.3562 | 0.51200 | 0.0034 | 41.566 |
| | 40 | 400 | 30 | 0.0064 | 39.1721 | 0.3456 | 0.47785 | 0.0035 | 41.452 |
| | 50 | 400 | 30 | 0.0071 | 37.7211 | 0.3365 | 0.46580 | 0.0036 | 41.249 |
| | 60 | 400 | 30 | 0.0081 | 37.3933 | 0.3214 | 0.43250 | 0.0037 | 40.944 |
| | 70 | 400 | 30 | 0.0083 | 36.2496 | 0.3125 | 0.42230 | 0.0039 | 40.800 |
| 6% chill | 30 | 400 | 30 | 0.0087 | 41.2096 | 0.4514 | 0.45148 | 0.0070 | 43.085 |
| | 40 | 400 | 30 | 0.0092 | 40.7242 | 0.4425 | 0.44250 | 0.0072 | 42.781 |
| | 50 | 400 | 30 | 0.0105 | 39.5762 | 0.4321 | 0.43210 | 0.0075 | 42.441 |
| | 60 | 400 | 30 | 0.0125 | 38.0618 | 0.4215 | 0.42150 | 0.0079 | 42.047 |
| | 70 | 400 | 30 | 0.0142 | 36.9542 | 0.4125 | 0.41250 | 0.0079 | 41.970 |
| 3% chill | 30 | 400 | 30 | 0.0108 | 44.1522 | 0.512 | 0.35621 | 0.0083 | 49.218 |
| | 40 | 400 | 30 | 0.011 | 43.8764 | 0.4778 | 0.34560 | 0.0084 | 48.898 |
| | 50 | 400 | 30 | 0.013 | 42.9748 | 0.4658 | 0.33650 | 0.0086 | 48.659 |
| | 60 | 400 | 30 | 0.0135 | 41.8303 | 0.4325 | 0.32140 | 0.0089 | 48.427 |
| | 70 | 400 | 30 | 0.0154 | 41.6184 | 0.4223 | 0.31258 | 0.0091 | 48.178 |
| As cast chill end | 30 | 400 | 30 | 0.0144 | 42.1581 | 0.5551 | 0.40010 | 0.0095 | 44.959 |
| | 40 | 400 | 30 | 0.0156 | 41.8303 | 0.5214 | 0.38220 | 0.0097 | 44.597 |
| | 50 | 400 | 30 | 0.0166 | 40.7242 | 0.5125 | 0.37002 | 0.0099 | 44.451 |
| | 60 | 400 | 30 | 0.018 | 39.5762 | 0.5021 | 0.35860 | 0.0102 | 44.265 |
| | 70 | 400 | 30 | 0.0191 | 39.1721 | 0.4896 | 0.34470 | 0.0112 | 44.096 |

2.1.2 Coefficient of friction discussion

The coefficient of friction is maximum for the 30N load on the pin and it gradually decreases as the load increases to 70N as shown in figure 5. Coefficient friction is vice-versa of the wear rate as shown in equation 4. The increase in the wear rate at 12wt.% is analyzed by its morphological study of the wear surface of the specimens. Hence 9wt.% of zircon and 12wt.% of zircon are selected for morphological analysis.

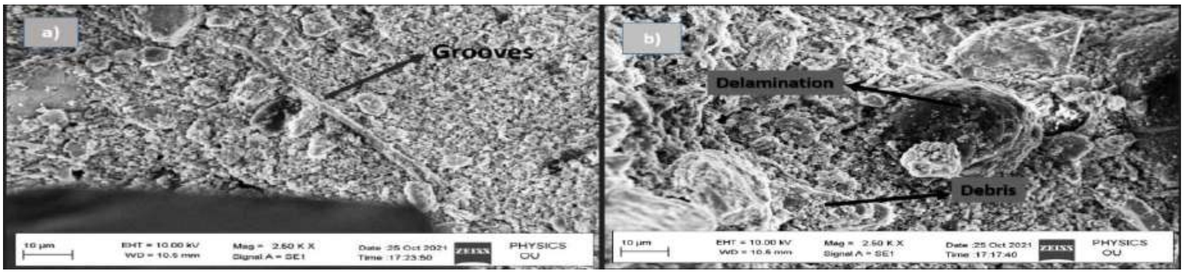
2.1.3 Morphological study

The surface morphology of the worn surface of the specimens is analyzed using FESEM at a magnification of 2.5K X resolution. It is observed that 9wt.% zircon has a homogenous mixture of matrix (LM13) and reinforcements (Zircon and carbon) but there are minor grooves observed due to sliding but there is no delamination and erosion of layers which makes composite pin withstand high wear resistance and hardness. But at 12wt.% of Zircon, it is observed that due to nucleation occurring at the interface of the matrix and the reinforcements, the tribo-layers wear out and oxidation happens which leads to delamination of the composite pin which is observed in Figure 6.




a) main effects plot for means (wear rate); b) main effects plot for means (COF); c) interaction plot for wear rate; d) interaction plot for COF

**Fig. 5**. - Dependence of load on wear rate, COF




a) 9wt.% of zircon, b) 12wt.% of zircon

**Fig. 6. -** Surface microstructure

2.1.4 Statistical analysis

For loads of 30 N and 9 Wt. % Zircon, the lowest wear rate is observed. Table 8.3 shows the effects of wear loss, COF, and wear rate on the Zircon's SN ratio values and the Load applied. It indicates that the expected and obtained results are more than 95% in agreement. In Taguchi's method, "Smaller is better" is taken into account to determine the wear rate optimal values because analysis calls for the lowest possible wear rate. The wear rate is observed to increase as the load increases, with the load of 30N and 9Wt.% Zircon showing the lowest wear rate. For various combinations of Zircon and applied force, the SN ratio of Wear loss, COF, and Wear rate is shown in Table 6.

**Table 6.** SN ratio of Wear loss, COF, and Wear rate

| Wear parameter | Wear loss | | COF | | Wear rate | |
|---|---|---|---|---|---|---|
| Level | Zircon | Load applied | Zircon | Load applied | Zircon | Load applied |
| 1 | 35.570 | 40.740 | 5.751 | 6.952 | 39.87 | 43.855 |
| 2 | 37.970 | 40.350 | 6.726 | 7.346 | 41.21 | 43.595 |
| 3 | 39.310 | 39.320 | 7.294 | 7.564 | 42.46 | 43.374 |
| 4 | 42.890 | 38.350 | 9.522 | 7.906 | 48.67 | 43.104 |
| 5 | 40.691 | 37.670 | 8.620 | 8.146 | 44.47 | 42.812 |
| Delta | 7.31 | 3.05 | 3.770 | 1.195 | 8.82 | 1.032 |
| Rank | 1.0 | 2.0 | 1.0 | 2.0 | 1.0 | 2.0 |

2.1.5 Regression analysis and analysis of variance (ANOVA)

Regression correlations have been established using the wear rate as the output and the Zircon content as the input for loads of 30N, 40N, 50N, 60N, and 70N. Equations (5), (6), and (7) indicate the regression equations for wear loss, COF, and wear rate, respectively. The Analysis of Variance (ANOVA) approach is used to assess the influence of numerous characteristics causing wear while accounting for degrees of freedom (DOF). Two-way regression analysis is taken into account for the investigation. Since both Zircon and Load effects on the wear metrics I, e Wear loss, COF, and wear rate are investigated. Table 7 shows the findings of the ANOVA test for wear rate, respectively. When performing regression investigations, the F and P values of the sources are taken into consideration. It has been observed that the value of the Load-applied source is less than the value of the Zircon content contribution. Therefore, COF, wear rate, and wear loss are influenced by Zircon content. Wear characteristics significantly benefit from the input of Zircon content. Regression correlations have been created using the wear rate as the output and the Zircon content as the input for loads of 30N, 40N, 50N, 60N, and 70N.

$$Wear\ loss = 0.0103 + 0.000111\ Applied\ load - 0.000706\ Zircon \quad (5)$$

$$COF = 0.583 - 0.00148\ Applied\ load - 0.0140\ Zircon \quad (6)$$

$$Wear\ rate = 0.00881 + 0.000021\ Applied\ load - 0.000446\ Zircon \quad (7)$$

**Table 7.** ANOVA (Two way) of Wear rate

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | Contribution (%) |
|---|---|---|---|---|---|---|
| Load applied | 4.0 | 0.000026 | 0.0000007 | 13.65 | 0.000 | 18.72075 |
| Zircon Content | 4.0 | 0.0001033 | 0.0000314 | 714.20 | 0.000 | 80.65523 |
| Error | 16.0 | 0.0000069 | 0.0000000 | | | 0.546022 |
| Total | 24.0 | 0.0001282 | | | | 100 |

2.1.6 Confirmative study of copper chill end specimens

A confirmative study is done based on regression equations obtained in statistical analysis using MINITAB software. Wear loss, COF, and wear rate equations give the relationship between the influencing factors and wear parameters. Since the Load applied and Zircon content influence wear parameters like wear loss, COF, and wear rate are being evaluated. The study is done by providing different values of Load and Zircon content to obtain the wear parameters in equations 5, 6, and 7. The resulting value is contrasted with the findings of the experiment. As indicated in Table 8, it can be observed that the findings obtained match each other with minimal inaccuracy.

**Table 8.** Confirmative study of copper chill end specimens

| Exp No. | Load applied (N) | Zircon content (Wt. %) | Statistical results | | | Experimental results | | |
|---|---|---|---|---|---|---|---|---|
| | | | Wear loss | COF | Wear rate | Wear loss | COF | Wear rate |
| 1 | 35 | 3.5 | 0.0117 | 0.4534 | 0.00798 | 0.0106 | 0.4689 | 0.456 |
| 2 | 45 | 4.5 | 0.0121 | 0.4246 | 0.00775 | 0.0125 | 0.4365 | 0.4258 |
| 3 | 55 | 5.5 | 0.0125 | 0.3958 | 0.00751 | 0.0121 | 0.4015 | 0.3985 |
| 4 | 65 | 6.5 | 0.0129 | 0.367 | 0.00728 | 0.0123 | 0.3652 | 0.3645 |
| 5 | 75 | 7.5 | 0.0133 | 0.3382 | 0.00704 | 0.0135 | 0.3325 | 0.3421 |
| 6 | 85 | 8.5 | 0.0137 | 0.583 | 0.0068 | 0.0137 | 0.575 | 0.581 |

**2.2 Effect of sliding speed**

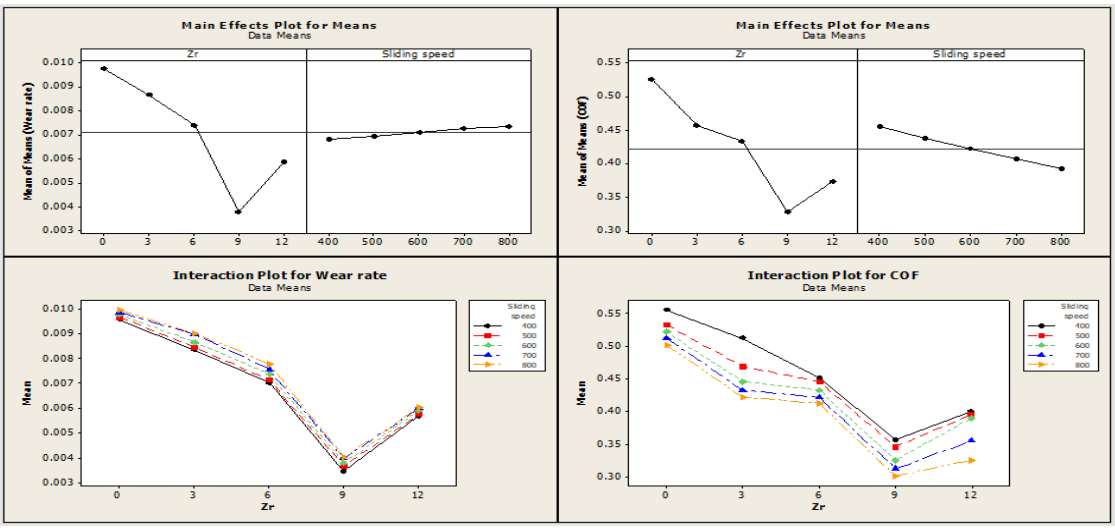
On the composite pin fabricated by copper chill casting, the impact of sliding speed is assessed. By keeping a constant track radius of 30 mm, the sliding speed is changed from 400 to 800 rpm in increments of 100 rpm. Table 9 illustrates that sliding speed affects the various percentages of reinforcement samples made from the copper chill. The effect of sliding speed and Zircon is shown in Table 10 and Figure 7. Wear loss and wear rate are related to sliding speed and inversely related to Zircon content up to a Wt. % of 9; then wear loss increases.

**Table 9.** Taguchi method for sliding speed and zircon content

| Factors /Levels | L1 | L2 | L3 | L4 | L5 |
|---|---|---|---|---|---|
| Factor 1 - Zircon Content (Wt. %) | 0 | 3 | 6 | 9 | 12 |
| Factor 2 - Sliding speed (rpm) | 400 | 500 | 600 | 700 | 800 |

**Table 10.** Sliding speed effect on Wear loss, COF, and wear rate for Copper chill end specimens

| | AL | RPM | TR | WL | SN (WL) | COF | SN COF | WR | WR (SN) |
|---|---|---|---|---|---|---|---|---|---|
| 12% chill | 30 | 400 | 30 | 0.0078 | 36.832 | 0.4001 | 5.1121 | 0.0056 | 5.1121 |
| | 30 | 500 | 30 | 0.009 | 36.363 | 0.3952 | 5.4736 | 0.0057 | 5.4736 |
| | 30 | 600 | 30 | 0.0092 | 35.972 | 0.3896 | 5.6566 | 0.0059 | 5.6566 |
| | 30 | 700 | 30 | 0.0105 | 35.809 | 0.3548 | 5.8095 | 0.0059 | 5.8095 |
| | 30 | 800 | 30 | 0.011 | 35.391 | 0.3254 | 5.9998 | 0.0060 | 5.9998 |
| 9% chill | 30 | 400 | 30 | 0.0062 | 39.331 | 0.3562 | 5.8146 | 0.0034 | 5.8146 |
| | 30 | 500 | 30 | 0.0071 | 39.015 | 0.3456 | 6.5821 | 0.0036 | 6.5821 |
| | 30 | 600 | 30 | 0.00736 | 38.159 | 0.3256 | 7.0211 | 0.0037 | 7.0211 |
| | 30 | 700 | 30 | 0.00745 | 37.271 | 0.3125 | 7.2803 | 0.0039 | 7.2803 |
| | 30 | 800 | 30 | 0.00765 | 36.618 | 0.3012 | 7.5061 | 0.0040 | 7.5061 |
| 6% chill | 30 | 400 | 30 | 0.0087 | 41.209 | 0.4514 | 6.9072 | 0.0070 | 6.9072 |
| | 30 | 500 | 30 | 0.0096 | 40.354 | 0.4456 | 7.0211 | 0.0071 | 7.0211 |
| | 30 | 600 | 30 | 0.0112 | 39.015 | 0.4325 | 7.2803 | 0.0073 | 7.2803 |
| | 30 | 700 | 30 | 0.01213 | 38.322 | 0.4215 | 7.5040 | 0.0075 | 7.5040 |
| | 30 | 800 | 30 | 0.01325 | 37.555 | 0.4124 | 7.6936 | 0.0077 | 7.6936 |
| 3% chill | 30 | 400 | 30 | 0.0108 | 44.152 | 0.512 | 8.9659 | 0.0083 | 8.9659 |
| | 30 | 500 | 30 | 0.0112 | 42.974 | 0.4687 | 9.2285 | 0.0084 | 9.2285 |
| | 30 | 600 | 30 | 0.01236 | 42.662 | 0.4456 | 9.7463 | 0.0086 | 9.7463 |
| | 30 | 700 | 30 | 0.01369 | 42.556 | 0.4325 | 10.103 | 0.0089 | 10.103 |
| | 30 | 800 | 30 | 0.01476 | 42.326 | 0.4214 | 10.422 | 0.0090 | 10.422 |
| As cast chill end | 30 | 400 | 30 | 0.0144 | 42.158 | 0.5551 | 7.9566 | 0.0095 | 7.9566 |
| | 30 | 500 | 30 | 0.0152 | 40.915 | 0.5325 | 8.0637 | 0.0096 | 8.0637 |
| | 30 | 600 | 30 | 0.0159 | 40.724 | 0.5214 | 8.1876 | 0.0097 | 8.1876 |
| | 30 | 700 | 30 | 0.0162 | 39.576 | 0.5123 | 9.0003 | 0.0098 | 9.0003 |
| | 30 | 800 | 30 | 0.017 | 39.172 | 0.5012 | 9.7516 | 0.0099 | 9.7516 |




a) main effects plot for means (wear rate); b) main effects plot for means (COF); c) interaction plot for wear rate; d) interaction plot for COF

**Fig. 7.** – Dependence of sliding speed effect on wear loss, COF, and wear rate for copper chill end specimens

2.2.1 Statistical analysis

The software MINITAB is used to statistically assess the experimental outcomes. In Taguchi's DOE, "Smaller is better" is taken into account while calculating the SN ratio for an L25 orthogonal array. It has been observed that the wear rate decreases as the sliding speed rises. Zircon and sliding speed have an impact on wear rate, COF, and wear loss. Because Zircon content delivers a higher delta value for all wear parameters, the Zircon effect has a considerable impact on wear loss, COF, and wear rate. The SN ratio of Wear rate for various combinations of Zircon and sliding speed is shown in Table 11.

**Table 11.** SN ratio plot for Wear rate of copper non-chill end specimens

| Wear parameter | Wear loss | | COF | | Wear rate | |
|---|---|---|---|---|---|---|
| Level | Zircon | Sliding speed | Zircon | Sliding speed | Zircon | Sliding speed |
| 1 | 36.070 | 40.740 | 5.6100 | 6.9510 | 40.210 | 43.840 |
| 2 | 38.080 | 39.920 | 6.8410 | 7.2741 | 41.220 | 43.650 |
| 3 | 39.290 | 39.310 | 7.2811 | 7.5780 | 42.660 | 43.430 |
| 4 | 42.930 | 38.711 | 9.6930 | 7.9390 | 48.460 | 43.191 |
| 5 | 40.510 | 38.210 | 8.5920 | 8.2751 | 44.640 | 43.090 |
| Delta | 6.86 | 2.52 | 4.083 | 1.324 | 8.25 | 0.75 |
| Rank | 1 | 2 | 1 | 2 | 1 | 2 |

2.2.2 Regression analysis

The equation gives a regression equation using the wear rate as an output parameter, the sliding speed, and the Zircon content as input factors. The relationship between Zircon and sliding speed is observed in Table 12. Zr content has been discovered to be a potential wear rate parameter.

$$Wear\ loss\ =\ 0.0101\ +\ 0.000008\,Sliding\ speed\ -\ 0.000604\,Zircon \tag{8}$$

$$COF = 0.605\ -\ 0.000154\,Sliding\ speed\ -\ 0.0143\,Zircon \tag{9}$$

$$Wear\ rate = 0.00878\ +\ 0.000002\,Sliding\ speed\ -\ 0.000411\,Zircon \tag{10}$$

The Analysis of Variance (ANOVA) approach is used to assess the influence of numerous characteristics causing wear while accounting for degrees of freedom (DOF). Table 12 displays the findings of the ANOVA test for wear rate. The contribution of the sliding speed is significant in the wear rate.

**Table 12.** ANOVA (Two way) for wear rate of copper chill end

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | Contribution (%) |
|---|---|---|---|---|---|---|
| Sliding speed | 4 | 0.0000010 | 0.0000003 | 37.30 | 0.000 | 0.890472 |
| Zircon Content | 4 | 0.000111 | 0.0000278 | 3978.91 | 0.000 | 98.84239 |
| Error | 16 | 0.0000001 | 0.0000000 | | | 0.089047 |
| Total | 24 | 0.0001123 | | | | 100 |

2.2.3 Confirmative study for the Sliding speed effect on copper chill end specimens.

Given that the sliding speed and Zircon content are key considerations for assessing wear properties including wear loss, COF, and wear rate. The study is done by providing different values of sliding speed and Zircon content to obtain the wear parameters in equations 8, 9, and 10. The obtained value is compared with experimental results. It is observed that the obtained results match each other with negligible errors as shown in table 13.

**Table 13.** Confirmative study of silicon carbide chill end specimens of copper chill end

| Exp No. | Sliding speed (rpm) | Zircon content (Wt. %) | Statistical results | | | Experimental results | | |
|---|---|---|---|---|---|---|---|---|
| | | | Wear loss | COF | Wear rate | Wear loss | COF | Wear rate |
| 1 | 450 | 3.5 | 0.0115 | 0.1381 | 0.0082 | 0.0118 | 0.1379 | 0.00842 |
| 2 | 550 | 4.5 | 0.0117 | 0.3064 | 0.0080 | 0.0011 | 0.3065 | 0.00804 |
| 3 | 650 | 5.5 | 0.0119 | 0.4747 | 0.0078 | 0.0112 | 0.4715 | 0.00783 |
| 4 | 750 | 6.5 | 0.0121 | 0.643 | 0.0076 | 0.0126 | 0.6415 | 0.00765 |
| 5 | 850 | 7.5 | 0.0123 | 0.8113 | 0.0074 | 0.0121 | 0.8122 | 0.00742 |
| 6 | 950 | 8.5 | 0.0125 | 0.9796 | 0.0071 | 0.0125 | 0.9725 | 0.00711 |

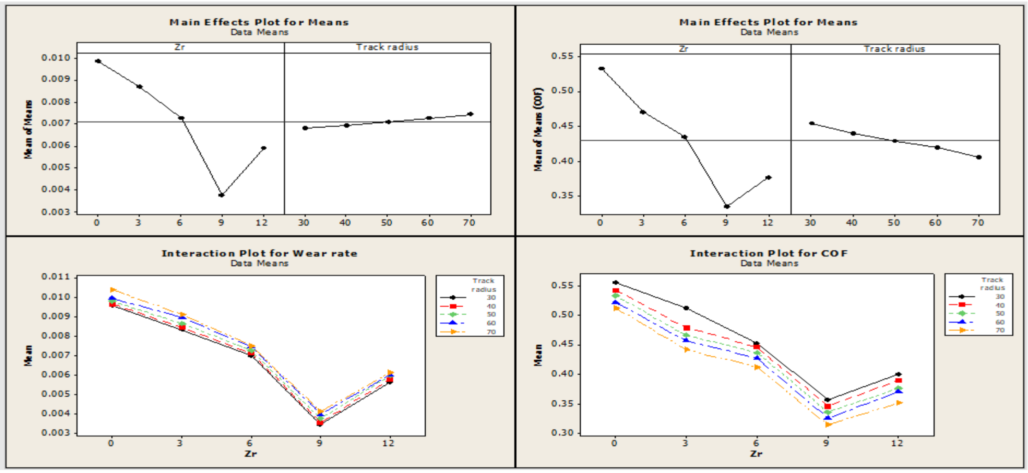
**2.3 Effect of track radius**

Wear loss, coefficient of friction, and wear rate are affected by sliding distance. The experiment is carried out with a 30 N load and 400 rpm sliding speed. With a 10 mm increment, the track radius ranges from 30 to 70 mm. It has been observed that wear rate and wear loss are inversely correlated with the coefficient of friction and proportionate to sliding distance (COF). Figure 8 depicts the sliding distance that affects the wear rate. It has been noted that as Zircon content rises from 3 Wt. % to 9 Wt. %, the wear rate lowers until it reaches 12 Wt. %. Zircon combined with 400 rpm and 9 Wt. % produces greater outcomes than other combinations. Sliding distance impact on wear rate, COF, and wear loss of the composite pin is assessed. The pin is loaded under a 30N load. The experiment is optimized using an L25 orthogonal array as given in Table 14 to evaluate the impact of sliding distance on wear behavior.

**Table 14.** Effect of track radius on wear rate

| | AL | RPM | TR | WL | WL SN | COF | COF SN | WR | WR SN |
|---|---|---|---|---|---|---|---|---|---|
| 12% chill | 30 | 400 | 30 | 0.0078 | 36.8328 | 0.4001 | 5.1121 | 0.005645 | 40.3809 |
| | 30 | 400 | 40 | 0.0081 | 36.7129 | 0.3896 | 5.3152 | 0.005789 | 40.3059 |
| | 30 | 400 | 50 | 0.0085 | 36.5363 | 0.3758 | 5.4720 | 0.005969 | 40.1888 |
| | 30 | 400 | 60 | 0.009 | 36.4205 | 0.3698 | 5.6566 | 0.006012 | 40.0366 |
| | 30 | 400 | 70 | 0.0101 | 36.0269 | 0.3512 | 5.8061 | 0.006121 | 39.6761 |
| 9% chill | 30 | 400 | 30 | 0.0062 | 39.3315 | 0.3562 | 5.8146 | 0.00346 | 41.5663 |
| | 30 | 400 | 40 | 0.0065 | 39.1721 | 0.3456 | 6.3951 | 0.003556 | 41.4608 |
| | 30 | 400 | 50 | 0.0068 | 38.3443 | 0.3356 | 6.6360 | 0.003756 | 41.2516 |
| | 30 | 400 | 60 | 0.0075 | 38.0618 | 0.3256 | 6.8036 | 0.003987 | 40.9509 |
| | 30 | 400 | 70 | 0.0082 | 37.7882 | 0.3145 | 7.1073 | 0.004125 | 40.7953 |
| 6% chill | 30 | 400 | 30 | 0.0087 | 41.2096 | 0.4514 | 6.9072 | 0.00701 | 43.0856 |
| | 30 | 400 | 40 | 0.0089 | 41.0122 | 0.4456 | 7.0211 | 0.007123 | 42.9467 |
| | 30 | 400 | 50 | 0.0091 | 40.8001 | 0.4365 | 7.2003 | 0.007258 | 42.7837 |
| | 30 | 400 | 60 | 0.0094 | 40.5190 | 0.4269 | 7.3935 | 0.007456 | 42.5499 |
| | 30 | 400 | 70 | 0.0112 | 39.0156 | 0.4121 | 7.6999 | 0.007512 | 42.4849 |
| 3% chill | 30 | 400 | 30 | 0.0108 | 44.1522 | 0.512 | 8.9659 | 0.00835 | 49.2185 |
| | 30 | 400 | 40 | 0.011 | 43.7417 | 0.4789 | 9.2285 | 0.008452 | 48.9808 |
| | 30 | 400 | 50 | 0.0121 | 43.3498 | 0.4658 | 9.4836 | 0.008658 | 48.5055 |
| | 30 | 400 | 60 | 0.0125 | 42.4988 | 0.4569 | 9.7463 | 0.008963 | 47.9871 |
| | 30 | 400 | 70 | 0.0129 | 41.7237 | 0.4412 | 10.047 | 0.009125 | 47.6915 |
| As cast chill end | 30 | 400 | 30 | 0.0144 | 42.1581 | 0.5551 | 7.9566 | 0.009571 | 44.9667 |
| | 30 | 400 | 40 | 0.0146 | 41.8303 | 0.5423 | 8.1876 | 0.009654 | 44.7479 |
| | 30 | 400 | 50 | 0.0149 | 41.4116 | 0.5326 | 8.5009 | 0.009785 | 44.4808 |
| | 30 | 400 | 60 | 0.0151 | 40.9151 | 0.5214 | 8.6407 | 0.009958 | 44.4189 |
| | 30 | 400 | 70 | 0.0158 | 39.9136 | 0.5125 | 9.0889 | 0.01038 | 44.2636 |

From Figure 8, it is observed that wear loss and wear rate are proportional to the load applied and inversely proportional to Zircon content till 9Wt.% of Zircon, with further addition of Zircon the wear loss increases.




a) main effects plot for means (wear rate); b) main effects plot for means (COF); c) interaction plot for wear rate; d) interaction plot for COF

**Fig. 8. -** Dependence of track radius effect of on wear rate

2.3.1 Statistical analysis

The SN ratio for wear loss, COF, and wear rate are shown in Table 15 respectively. In Taguchi's method, "Smaller is better" is taken into account to determine the wear rate's optimal values because the lowest possible wear rate is desired. The wear rate is observed to increase as the load increases, with the load of 30N and 9Wt% Zircon showing the lowest wear rate. Table 16 represents the SN ratio of Wear loss, COF, and Wear rate for different combinations of Zircon and track radius.

**Table 15.** SN ratio of wear loss, COF, and wear rate

| Wear parameter | Wear loss | | COF | | Wear rate | |
|---|---|---|---|---|---|---|
| Level | Zircon | Track radius | Zircon | Track radius | Zircon | Track radius |
| 1 | 36.510 | 40.740 | 5.4720 | 6.9510 | 40.120 | 43.840 |
| 2 | 38.540 | 40.490 | 6.5510 | 7.2300 | 41.210 | 43.690 |
| 3 | 40.510 | 40.090 | 7.2440 | 7.4590 | 42.770 | 43.440 |
| 4 | 43.091 | 39.680 | 9.4940 | 7.6480 | 48.480 | 43.190 |
| 5 | 41.250 | 38.890 | 8.4750 | 7.9500 | 44.580 | 42.980 |
| Delta | 6.59 | 1.84 | 4.022 | 0.999 | 8.36 | 0.86 |
| Rank | 1 | 2 | 1 | 2 | 1 | 2 |

2.3.2 Regression analysis

For track radii of 30mm, 40mm, 50mm, 60mm, and 70mm, regression correlations have been created using the wear rate as the output and the Zircon content as the input as shown in equations 11,12 and 13.

$$Wear\ loss\ =\ 0.0117\ +\ 0.000048\,Track\ radius\ -\ 0.000599\,Zircon \tag{11}$$

$$COF = 0.583\ -\ 0.00120\,Track\ radius\ -\ 0.0149\,Zircon \tag{12}$$

$$Wear\ rate = 0.00893\ +\ 0.000017\,Track\ radius\ -\ 0.000423\,Zircon \tag{13}$$

Table 16 displays the findings of the ANOVA test for wear rate. The contribution of the sliding speed is significant in the wear rate.

**Table 16**. ANOVA (Two way) for wear rate of copper chill end

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | Contribution (%) |
|---|---|---|---|---|---|---|
| Track radius | 4 | 0.0000014 | 0.0000003 | 49.17 | 0.00 | 1.214224 |
| Zircon Content | 4 | 0.0001138 | 0.0000284 | 4068.47 | 0.00 | 98.69905 |
| Error | 16 | 0.0000001 | 0.000000 | | | 0.08673 |
| Total | 24 | 0.0001153 | | | | 100 |

2.3.3 Confirmative study for the Sliding distance effect on copper chill end specimens

Sliding distance and Zircon content are the influencing factors to evaluate the wear parameters like wear loss, COF, and wear rate. The study is done by providing different values of Sliding distance and Zircon content to obtain the wear parameters in equations 11, 12, and 13. The obtained value is compared with experimental results. It is observed that the obtained results match each other with negligible errors as shown in table 17.

**Table 17.** Confirmative study of silicon carbide chill end specimens of copper chill end

| Exp No. | Track radius (mm) | Zircon content (Wt. %) | Statistical results | | | Experimental results | | |
|---|---|---|---|---|---|---|---|---|
| | | | Wear loss | COF | Wear rate | Wear loss | COF | Wear rate |
| 1 | 35 | 3.5 | 0.01128 | 0.5395 | 0.0080 | 0.0111 | 0.5379 | 0.0080 |
| 2 | 45 | 4.5 | 0.01116 | 0.5271 | 0.0077 | 0.0113 | 0.5265 | 0.0077 |
| 3 | 55 | 5.5 | 0.01104 | 0.5146 | 0.0075 | 0.0110 | 0.5141 | 0.0075 |
| 4 | 65 | 6.5 | 0.01092 | 0.5022 | 0.0072 | 0.0105 | 0.5015 | 0.0072 |
| 5 | 75 | 7.5 | 0.01080 | 0.4898 | 0.0070 | 0.0108 | 0.4802 | 0.0704 |
| 6 | 85 | 8.5 | 0.01068 | 0.4774 | 0.0067 | 0.0106 | 0.4725 | 0.0067 |

## Conclusion

By considering experimental, and statistical studies on LM13/Zircon/Carbon Hybrid metal matrix composites following conclusions have been made.

The Stir casting process and chill casting technique are effective methods to fabricate the hybrid metal matrix composite and to enable unidirectional solidification respectively.

9wt.% of zircon/3wt.% carbon/LM13 provides the minimal wear rate than other specimens.

Wear rate is directly proportional to the applied load, sliding speed, and sliding distance, and COF is inversely proportional to the applied load, sliding speed, and sliding distance.

By analyzing influencing wear parameters, Zircon is the prominent factor that influences the wear rate than other parameters.

The morphology of the surface of the specimens is analyzed, 9wt.% of zircon / 3wt.% of carbon / LM13 provides minimal deformation and grooves than other combination morphologies.

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