Comparative Tribological Analyses of Hybrid Composite for Disc-Brake Rotor Application

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Abstract - *In the field of material and engineering, there is a great impact in the innovation of composite material. Because of its superior properties such as high tensile strength, lightweight, fatigue resistance and wear resistance, this has its applications in aerospace, aircrafts, underwater, automobile, turbine blades and brake pads. Metal matrix composite such as boron nitride, carbon fiber and redmud composite have become more attractive due to the mechanical properties of reinforced materials. In this research to fabrication of metal matrix composite with various weight percentages of redmud (RM), boron nitride (BN) and carbon fiber (CF) content in aluminium. Many more fabrication techniques are available for the fabrication of metal matrix composites. Stir-casting method is simple method for fabrication, low-cost and used for automated production. The fabricate composite were tested on response surface methodology (RSM) as per ASTM standards to calculate and optimized the tribological behavior of the composite such as wear & co-efficient of friction.*

Keywords: AL6063, BN, CF, RM, Minitab, Stir casting, Pin-on-disc, FEM.

1. INTRODUCTION

Materials' selection and its resisting load capability have been played the principal role in the lifetime of the product at the complicated real-time applications such as impact loading conditions, rotodynamic structural applications, etc. Because of this primary factor, most of the researches have been dealt with the materials based investigation in the complicated applications. In this work also investigated one of the complicated applications, which is a rotodynamic nature-based disc rotor application is selected as the fundamental platform. Due to the rotodynamic platform, this kind of rotor disc has been provided the utmost care in the perspective of high load withstanding capability, high stiffness to weight ratio, high strength to weight ratio, low thermal conductivity, and high melting point. Therefore in this work the paramount heed is given to the material's selection, in this regard the standard field works were carried out and thus the suitable material was obtained. The predominant material is chosen as Metal-Matrix Composite, in which Aluminium Alloy 6063 is used as primary agent and boron nitrate, carbon fiber materials are used as core materials. Two predominant engineering approaches such as experimental test and advanced computational FEA analysis are involved in this investigation, in which the conventional method, i.e., Pin-on-Disc based experimental test is used for the estimation of frictional co-efficient, wear rate and computational composite tool is used for the construction of metal matrix composite thereby the FEA analyses are carried out for the estimations of shear stress, deformations, strain energy, and all the principal stresses. The ultimate uniqueness involved in this work is investigated the tribological behavior on advanced materials through latest computational techniques with the conventional test based initial conditions.

2. LITERATURE SURVEY

P. Natarajan and el to developed the Ni-Sic Nano composite coatings and calculate wear, surface roughness and micro hardness results by optimization technique [1]. A.Lotfy A.Daoud and el to prepare the AL-5%cu/BN/Si_3N_4 composite and analysis the micro structure, thermal and mechanical properties. Hardness property is improved on ALMMC [2]. Megalingam A Kumar A and at el to fabricate on AL6063/ Alumina/ Graphite/ Redmud are various weight %. Then calculate on wear and COF on Taguchi L27 method and they improve on 90% of wear and 48% of COF by using and improve the Redmud content [3]. Reddy MP and at el to calculate the structural, mechanical and thermal properties of AL-Cu-Li composites and to prepare the composite by using stir casting method [4]. R. Pramod and at el to explain the mechanical and tribological behaviour of silicon nitride reinforced with aluminium6063 metal matrix composites and to increase the wear properties compare the base material and increase the tensile strength of MMC [6]. Dr.S.V.S.Narayan Murty and at el to fabricate the AL7075-CF metal matrix composites by using stir casting method and that result is to increase the major %of CF content to decreases the hardness of MMC. So, we can choose only 3%of CF [7]. Yunhe Zhang and at el to fabricate the aluminium-CF metal matrix composite to calculate the mechanical properties and microstructure of the matrix material. Finally to capture the SEM image to find out the material bonding [8]. Rushikesh A. Khatavkar and at el to determine the wear behaviour of al2024-hBN composites by using stir casting methods. Finally to improve the hardness by improving hBN particles and improve wear resistance by adding 6%hBN particles with AL2024 [11].

3. Materials and methods

3.1. Fabrication components

- ✓ The base metal is chosen as aluminium 6063.
- ✓ The reinforcement is chosen as boron nitride particulates, carbon fiber and redmud particulates.
- ✓ With the base metal as Aluminium, the composite is to be fabricated with 3% volume of Boron nitride Particulates and 3%.of Carbon fiber and the redmud particles 4%.

3.2. Composite preparation

The stir casting method was utilized to create the composite example as it guarantees a progressively uniform circulation of the reinforcement particles. In this procedure, alloy (Al 6063) was first superheated over its melting temperature and afterward temperature is decreases gradually below the fluids temperature to maintain the aluminium alloy in the semi-fluid stage. At this temperature, the preheated BN particles of 3 % are constant (by weight) and carbon fiber particle of 3% average size of 23 µm and 45 µm respectively were introduced into the slurry and mixed using a high carbon steel stirrer. The composite slurry temperature was expanded to completely fluid state and automatic stirring was preceded to around five minutes at a normal mixing velocity of 250-400 rpm and 600⁰C temperature under secured organ gas. The BN particles help in dispersing the graphite particles consistently all through the matric composite.

3.3. Finite Element Analysis (FEA)

FEA is one the flexible approaches involved in the Computer Aided Engineering based investigation. In this investigation, the structural parameters on metal matrix composite based test specimens are underwent FEA simulations with the help of initial boundary conditions attained through experimental test. The predominant boundary and initial conditions are used for this complicated FEA simulations are: Pin load, Pin holds, Rotational Speed, ground to body support at disc and frictional coefficients. As per the ASTM-G99 the computational models are prepared and imposed in the FEA simulations with fine discretizations. To represent the rotational velocities of the disc, the transient structural tool is employed as platform of this simulation, in which the final time-step is given as 60s. To represent the pin hold set-up, the fixed support is provide at the circular boundary of the pin and thus the various pin loads are provided at the axial wise of the pin in Newtons. From the literature surveys, the materials' selection and their mechanical properties were collected and thus imposed in these comparative investigations.

4. RESULTS AND DISCUSSION

4.1. Wear testing

Response surface methodology-RSM methods give a collection of both statistical techniques and mathematical relationship between output responses with input parameters. This method is used here to study the relationship between the parameters (load, speed and time) and the response (dry sliding wear characteristics). A second order polynomial regression model is constructed to predict the relationship, which is shown in equation (1)

$$Y_u = b + \Sigma\, b_i x_{iu} + \Sigma\, b_{ij} x^2_{iu} + \Sigma\, b_{ij} x_{iu} x_{ju} \qquad (1)$$

Where y_u is the response and b, b_i, and bij are the coefficients. The b is a linear effect; b_i is the higher order effect and b_{ij} the interaction effect. A Central Composite Design (CCD) was chosen for deciding the dry sliding wear attributes of the created composite. The testing specimen dimensions are 30mm length and 10mm diameter. In the RSM, the quantity of parameters decides the quantity of experimental runs.

Table 1: Input Parameters and their Levels

Parameters	Unit	Level		
		I	II	III
Load (L)	Kg	2	3	4
Speed (S)	Rpm	400	600	800
Time (T)	Min	3.20	4.25	6.38

From table 1 for the three parameters (load, speed and time) selected in this study, 20 experimental runs were generated. A High and low level of load (2, 3 and 4 kg), speed (400,600and 800 rpm) and time (3.20, 4.25 and 6.368 min) were used as input in the CCD, and an experimental design was obtained with each parameter varied at three levels. The vast amounts of data have been generated by the traditional approach of experiment design in which one factor is varied at a time (load, speed, etc.). In this Approach, it is difficult to evaluate the combined effects of applied factors. This is the main reason why load has always been considered first in wear research, whilst other factors, e.g. speed, sliding distance and their combined effects (load and sliding distance, load and speed, and so on.), which may likewise be significant, have not been given the consideration they deserve. The wear test results are given the below table2.

Table 2: Results of wear test.

Ex. No	Applied Load (L)	Sliding Speed (S)	Sliding Time (T)	Wear rate for ALMMC	COF for ALMMC
1	20	400	6.38	0.1276	0.20
2	40	400	6.38	0.1432	0.22

3	20	800	6.38	0.2200	0.34
4	40	800	6.38	0.2679	0.38
5	20	400	3.20	0.0956	0.19
6	40	400	3.20	0.1272	0.19
7	20	800	3.20	0.1790	0.22
8	40	800	3.20	0.2019	0.30
9	20	600	4.25	0.1104	0.22
10	40	600	4.25	0.1654	0.18
11	30	400	4.25	0.1472	0.23
12	30	600	4.25	0.1291	0.21
13	30	600	6.38	0.1444	0.30
14	30	600	3.20	0.1063	0.22
15	30	600	4.25	0.1259	0.24
16	30	600	4.25	0.1299	0.25
17	30	600	4.25	0.1245	0.23
18	30	600	4.25	0.1267	0.25
19	30	600	4.25	0.1351	0.26
20	30	600	4.25	0.1304	0.25

It is evident from the table2, among these parameters; Load is a dominant factor on the specific wear rate and speed for coefficient of friction. The influences of controlled factors on specific wear rate and coefficient friction is graphically represented in the following figure (1)

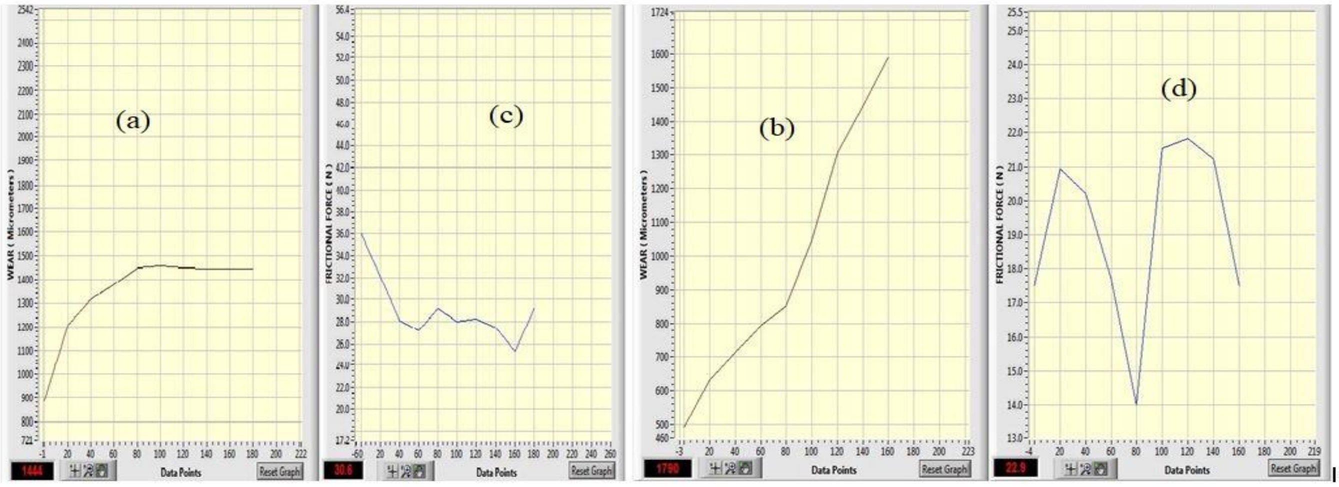

Fig.1. sample graph for (a) & (b) specific wear rate and (c) & (d) coefficient of friction

From the Fig.1.graphs explained Specific wear rate and coefficient of friction with respect to applied load, sliding speed, sliding time and sliding distance.

4.2. Optimization results

The experimental results and mathematical values calculated based on the plan of experiment and then the results analyzed with the help of Minitab (V16) software.

4.3. Specific wear rate-ALMMC

The following equation represents the regression equation (2) corresponding to quadratic model for specific wear.

$$\text{Wear (ALMMC)} = 0.2804 - 0.00365\,L - 0.001092\,S + 0.0479\,T + 0.000074\,L*L + 0.000001\,S*S0.00525\,T*T + 0.000001\,L*S + 0.000016\,L*T + 0.000023\,S*T \quad (2)$$

Table 3: Anova table for Wear test ALMMC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.032969	98.30%	0.032969	0.003663	64.42	0.000
Linear	3	0.025749	76.78%	0.024904	0.008301	145.99	0.000
L	1	0.002993	8.92%	0.002982	0.002982	52.44	0.000
S	1	0.017393	51.86%	0.018193	0.018193	319.95	0.000
T	1	0.005363	15.99%	0.003729	0.003729	65.58	0.000
Square	3	0.006701	19.98%	0.006582	0.002194	38.59	0.000
L*L	1	0.003734	11.13%	0.000128	0.000128	2.25	0.165

S*S	1	0.002612	7.79%	0.002681	0.002681	47.15	0.000
T*T	1	0.000356	1.06%	0.000316	0.000316	5.55	0.040
2-Way Interaction	3	0.000519	1.55%	0.000519	0.000173	3.04	0.079
L*S	1	0.000070	0.21%	0.000070	0.000070	1.22	0.294
L*T	1	0.000001	0.00%	0.000001	0.000001	0.01	0.925
S*T	1	0.000449	1.34%	0.000449	0.000449	7.89	0.019
Error	10	0.000569	1.70%	0.000569	0.000057		
Lack-of-Fit	4	0.000494	1.47%	0.000494	0.000123	9.89	0.008
Pure Error	6	0.000075	0.22%	0.000075	0.000012		
Total	19	0.033537	100.00%				
S = 0.0075406 R^2 = 98.30% R^2(adjusted)= 96.78% R^2(predicted)= 73.13% Press= 0.0090121							

From the ANOVA table 3, it is evident that the interaction effect of speed (S) has the most significant influence and with linear term of time (T) contributing 51.86 & 15.99% on the wear resistance respectively. The linear term of load (L), interaction square of load, speed and 2-way interaction of speed-time (S*T) has the further reasonable influence on specific wear contributing 8.92, 11.13, 7.79 and 1.34% respectively. The 2-way interaction of load-speed (L*S) load-time (L*T) and square of time (T^2) have the least significance on specific wear. The model presents high Determination coefficient of R^2=98.30% and adjusted R^2=96.78% value is close to the predicted R2.

4.4. Co-efficient of friction (ALMMC)

The regression equation for the co-efficient of friction is given by the equation (3)

COF (ALMMC) = 0.287+ 0.02215 L- 0.001312S- 0.0503 T- 0.000415 L*L + 0.000001S*S+ 0.00340 T*T+ 0.000006 L*S +0.00000L*T + 0.000063 S*T (3)

Table 4: Anova table for COF for ALMMC

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.032969	98.30%	0.032969	0.003663	64.42	0.000
Linear	3	0.025749	76.78%	0.024904	0.008301	145.99	0.000
L	1	0.002993	8.92%	0.002982	0.002982	52.44	0.000
S	1	0.017393	51.86%	0.018193	0.018193	319.95	0.000
T	1	0.005363	15.99%	0.003729	0.003729	65.58	0.000
Square	3	0.006701	19.98%	0.006582	0.002194	38.59	0.000
L*L	1	0.003734	11.13%	0.000128	0.000128	2.25	0.165
S*S	1	0.002612	7.79%	0.002681	0.002681	47.15	0.000
T*T	1	0.000356	1.06%	0.000316	0.000316	5.55	0.040

2-Way Interaction	3	0.000519	1.55%	0.000519	0.000173	3.04	0.079
L*S	1	0.000070	0.21%	0.000070	0.000070	1.22	0.294
L*T	1	0.000001	0.00%	0.000001	0.000001	0.01	0.925
S*T	1	0.000449	1.34%	0.000449	0.000449	7.89	0.019
Error	10	0.000569	1.70%	0.000569	0.000057		
Lack-of-Fit	4	0.000494	1.47%	0.000494	0.000123	9.89	0.008
Pure Error	6	0.000075	0.22%	0.000075	0.000012		
Total	19	0.033537	100.00%				
S = 0.0075406 R^2 = 98.30% R^2(adjusted)= 96.78% R^2(predicted)= 73.13% Press= 0.0090121							

It is evident from the ANOVA table 4 of co-efficient of friction (COF) that the linear term of speed (S), quadratic term of speed (S^2) and linear term of time (T) have significant influence on co-efficient of friction contributing 45.99, 23.42 and 8.93% respectively. The interaction effect of speed-time (S*T), load-speed (L*S) and linear terms of load (L) has reasonable influence on the co-efficient of friction contributing 6.43, 2.5 & 2.00%. The quadratic term of load (L^2), time (T^2) and interaction effect of load-time (L*T) has the least contribution, indicating their insignificance on COF. The model presents high determination coefficient value, R^2=90.82%, indicating good model and its significance. It shows that there exists high correlation between the experimental and the predicted values. Also, the adjusted R^2value is 82.56%.

4.5: Multi objective optimization by grey relation grade

The AL6063 composite material Wear rate & Co-efficient of friction was investigated on multi objective optimization. That is to minimize the Ws & COF. The input parameters are Load (L), Speed(S), and Time (T). Grey relation grade is used the multi objective problem is converted to single objective problem. The RSM is used to measure the influence of process parameters on experimental result of single response. In this problem two responses considered are Ws and COF. Using GRD different units of measurement responses converted into single objective problem. For the data processing from the table 2, the minimum and maximum values of each response are considered. Wear and co-efficient of friction is dominant characteristics for which 'larger-the-better' characteristic relation is used. This can be normalized by equation (4),

$$Y^*i\ (k) = \frac{\max Yi(k) - Yi(k)}{\max Yi(k) - \min Yi(k)} \qquad (4)$$

After the data processing using above equation, the sequences are given in the table 5.
Now, the deviation sequence $\delta_{0i\,(k)}$ is for the corresponding reference sequence $Y^*_{0(k)}$ and the comparability sequence $Y^*_{i\,(k),}$ is found by, equation (5),

$$\delta 0i\ (k) = |Y^*0(k) - Y^*i\ (k)\ | \qquad (5)$$

The results of all δ_{0i} for i=1–20 are listed in table 5.

Table 5: The sequence of each performance characteristic after data processing

Ex. No	Wear Y^*_I (k)	COF Y^*_i (k)	Wear δ_{0i}	COF δ_{0i}
1	0.81428	0.9	0.185722577	0.100000000
2	0.72374	0.8	0.276262333	0.200000000
3	0.278	0.2	0.721996518	0.800000000
4	0	0	1	1.000000000
5	1	0.95	0	0.050000000
6	0.8166	0.95	0.183401045	0.050000000
7	0.51596	0.8	0.484039466	0.200000000
8	0.38305	0.4	0.616947185	0.600000000
9	0.9141	0.8	0.085896692	0.200000000
10	0.59489	1	0.405107371	0.000000000
11	0.70052	0.75	0.299477655	0.250000000
12	0.80557	0.85	0.194428323	0.150000000
13	0.71677	0.4	0.28322693	0.600000000
14	0.9379	0.8	0.062100987	0.200000000
15	0.82414	0.7	0.175856065	0.300000000
16	0.80093	0.65	0.199071387	0.350000000
17	0.83227	0.75	0.167730702	0.250000000
18	0.8195	0.65	0.180499129	0.350000000
19	0.77075	0.6	0.229251306	0.400000000
20	0.79803	0.65	0.201973302	0.350000000

From table 5, $\delta_{max\ (k)}$ and $\delta_{min\ (k)}$ are obtained as follows, equation (6),

$$\eta\, i\,(k) = \frac{\delta min + \lambda * \delta max}{\delta 0i\,(k) + \lambda * \delta max} \qquad (6)$$

Where, δ_{min} and δ_{max} is the deviation sequence of minimum and maximum value $\delta_{0i\ (k)}$. The limit of identification coefficient λ is $0 \leq \lambda \geq 1$. The λ value is assumed 0.5.Final GRG value is calculated on below equation (7),

$$\gamma i = \frac{1}{N} \sum_{N=0}^{N} \eta i(k) \qquad (7)$$

Where the γ_i is highest value of wear and COF and number of experiments in N. The highest value of GRG is 0.954545 for the experiment number 5 from the table (6).

Table 6: The Grey relational coefficients and Grey relation grade for Composition (B)

Ex. No	ALMMC			
	Wear $\eta_{\ i\ (k)}$	COF $\eta_{\ i\ (k)}$	WGRG $\gamma_{\ i}$	Rank
1	0.72915785	0.8333333	0.7812455	5
2	0.64411215	0.7142857	0.6791989	10
3	0.409166469	0.3846153	0.3968909	19
4	0.333333333	0.3333333	0.3333333	20
5	1	0.9090909	0.9545454	1
6	0.73163482	0.9090909	0.8203628	2
7	0.508109702	0.7142857	0.6111977	16
8	0.44764874	0.4545454	0.4510970	18
9	0.853392769	0.7142857	0.7838392	4
10	0.552420648	1	0.7762103	6
11	0.625408348	0.6666666	0.6460375	14
12	0.720016715	0.7692307	0.7446237	7
13	0.638384587	0.4545454	0.5464650	17
14	0.889519876	0.7142857	0.8019027	3
15	0.73980249	0.625	0.6824012	9
16	0.715234537	0.5882352	0.6517349	12
17	0.748804867	0.6666666	0.7077357	8
18	0.734754797	0.5882352	0.6614950	11
19	0.6856347	0.5555555	0.6205951	15
20	0.712277801	0.5882352	0.6502565	13

The higher GRG values indicate multiple output responses characteristics for the corresponding input parameters. In the present work, AL6063 composite multiple response result has been converted into optimization of a GRG. Thus, the multi-response optimization problem is reduced to a single objective function. The mean value of the

GRG for each level of input parameters, and the total mean value of the GRG is showed in tables 7.

Table 7: Ranking of ALMMC input parameters

	Levels	Load	Speed	Time
ALMMC	-1	0.7055	0.7763	0.7278
	0	0.6713	0.6934	0.6925
	1	0.6120	0.4481	0.5474
	Mean	0.6630	0.6393	0.6559
	Ranking	3	1	2

From the larger value of the GRG are the optimal value and its selected. In addition to this, the total mean of GRG for all the experiments is calculated to find influence of input parameters which are denoted by rank.

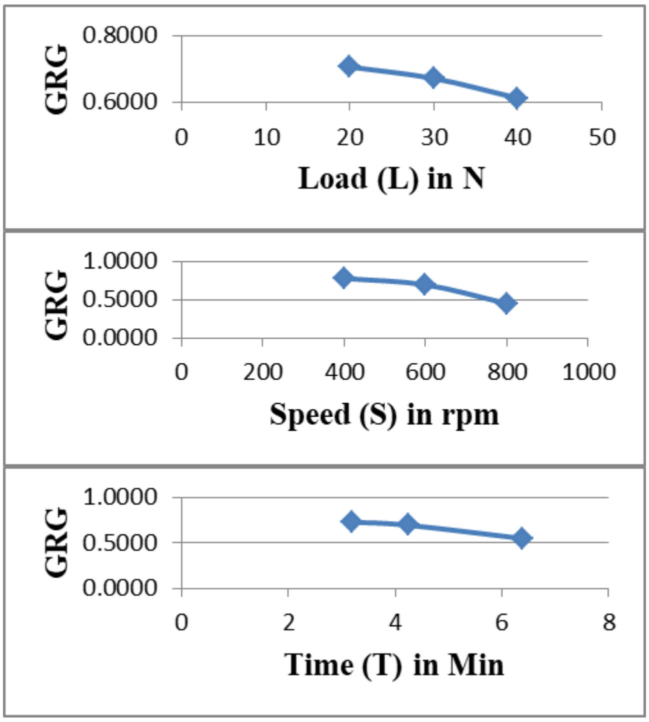

Figure2. Mean effective Plots of GRG in ALMMC

Figures 2 graphically represent the grey relational grades (GRGs) for Composition A & B in mean effect plot. From the GRGs and figures 2, the input parameters are found to be L (0)-S (-1)-T (-2), i.e. Load: 20 N, Speed 400rpm, and Time: 3.20Min.

Table 8: Result of confirmation test

Ex. No	Optimum value of ALMMC		
	Initial	Experimental	Error %
Wear	0.1276	0.1249	2.1
COF	0.20	0.19	5

4.6. Finite Element Analysis Results

The FEA results are computed on the pin-on-disc's test specimen for the aforesaid boundary conditions. In this comprehensive analysis, the specific input conditions implemented are 2 kg weight on pin, fixed support is given at the pin and the rotational velocity of 400 RPM is given at the disc. Figure 5 is revealed the components involved in the wear test set-up, in which the pin dimensions are 10 mm in diameter, 30 mm in height and the disc dimensions are 10 mm in thickness, 165 mm in diameter. The curvature is the design nature involved in this entire set-up so the curvature based fine mesh process is constructed, which is revealed in the figure 6. The total deformations and shear stress variations on the both pin and disc are clearly shown in the figures 7 and 8.

1) Base Materials

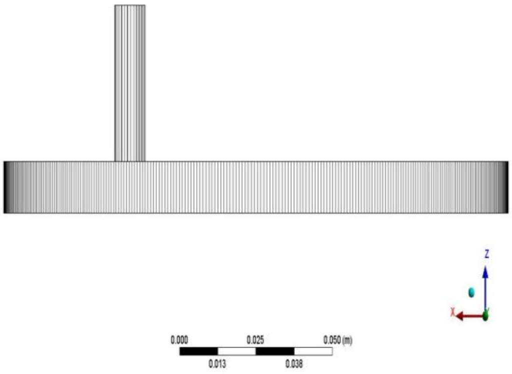

Fig 3: Computational model of entire test specimen

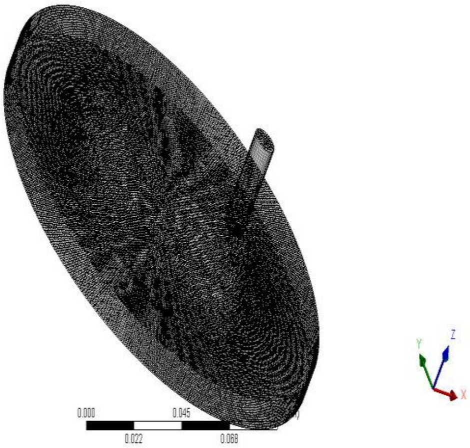

Fig 4: Discretized structure of entire test-up

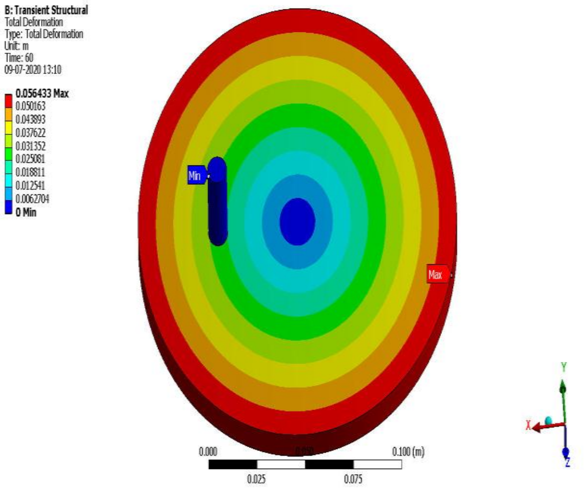

Fig 5: The variations of total deformation of entire test set-up

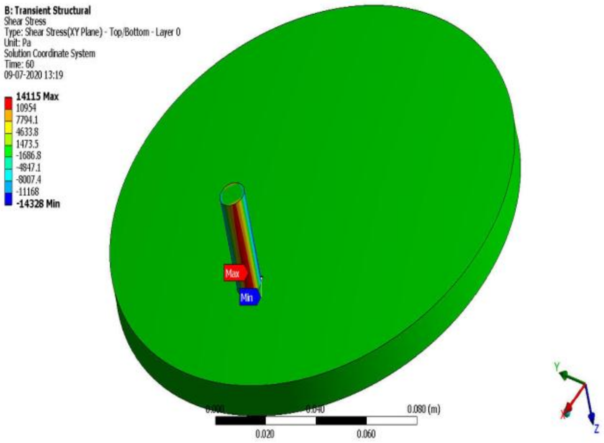

Fig 6: Shear Stress variations on the pin on disc experiment

2) Advanced Materials

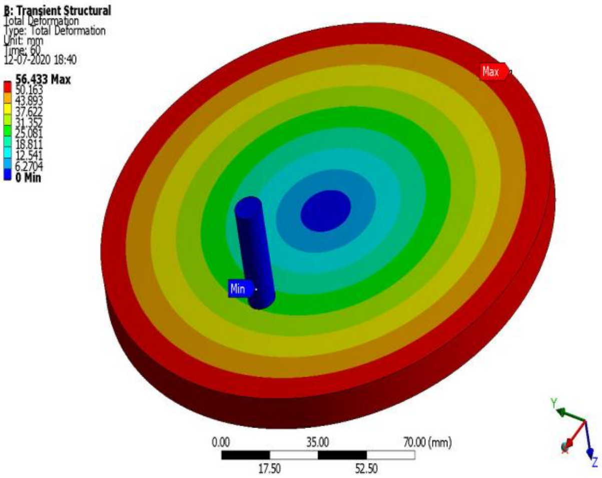

Fig 7: The variations of total deformation of entire advanced material test set-up

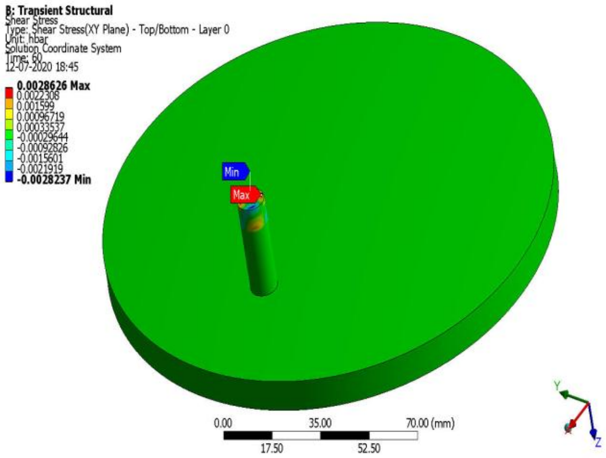

Fig 8: Shear Stress variations on the pin on disc experiment for advanced materials

Table 9: Comparative Analysis

Material Name	Shear stress (Pa)
Base Material	28626
Advanced Material	14115

5. CONCLUSIONS

The wear properties of aluminium6063 matrix composites reinforced with boron nitride, carbon fiber and redmud has been investigated. The results have shown clearly that boron nitride, carbon fiber and redmud can serve as a cost effective and technically reliable reinforcement for the development of composites. The result of an examination concerning the tribological (wear) of an aluminum alloy based boron nitride, carbon fiber and redmud particulate reinforced composite. The aluminium metal matrix composite was fabricated by using the stir casting method. ANOVA was additionally applied to check the competence of the developed model and there was a good agreement subsists between the experimental and predicted outcomes. From ANOVA, the reinforcement weight percentage (%), load, sliding speed and time had influence on the total response that was confirmed. The developed model in the present study had good capability such that it can be used to predict the results with minimum error. Pilot studies were carried out in various percentage of reinforcement's among that the 3% BN, 3% carbon fiber and 4% redmud produce better results. The optimum input parameters are attained from GRG rank analysis. Again we compare the obtained input results through experimental setup and find out the minimum errors 2.1% which have been obtained before wear results. . In addition to that the FEA analyses are also computed through the help of experimental outcomes.

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