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A Comparative Study of Machine Learning Algorithms for Predicting Tribological Performance of Al7075/Si3N4 Metal Matrix Composites

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Abstract: *In this study, Al7075 alloy composites were made with Si3N4 particles using a stir-casting method. The small grains formed because of the Si3N4 particles. SEM images showed that these particles spread evenly with few clumps. More Si3N4 led to more particle clusters. SEM and EDS tests showed a good bond between the matrix and particles, with no new compounds forming. The composites became harder (up to 118 BHN), stronger (up to 281 MPa), and had better yield strength (up to 178 MPa), improving by 30.69%, 20.27%, and 13.18%, respectively. The wear rate and friction of the composites were tested with more Si3N4. The wear rate was 0.019, 0.0085, 0.0075, and 0.0065 mm3/m as Si3N4 increased from 3 to 12 wt. %. The friction was 0.45, 0.37, 0.32, and 0.28. Adding Si3N4 improved wear resistance by up to 46% and increased wear from 0.0052 to 0.0103 mm3/m with higher sliding speed from 1.5 to 3.5 m/s, while reducing friction by up to 65%, from 0.43 to 0.27. SEM images showed wear types like abrasion, oxidation, delamination, and melt wear. Wear maps were used to study how composites behaved under dry sliding. Different machine learning models like RF, GB, k-NN, SVR, and ANN were used to predict wear rate and friction. The models were tested using R2, MSE, RMSE, and MAE. The support vector regression model predicted wear rate and friction well, with 96.96% and 94.75% accuracy. The amount of Si3N4 was the key factor in predicting wear rate and friction.*

Keywords: Al7075, wear rate and friction, RF, GB, k-NN, SVR, and ANN

I. INTRODUCTION

Recent years have seen a very great change in the materials used for engineering applications. The "standard" or "conventional" engineering materials (which include metals and alloys) are monoliths, and so cannot be used where a combination of material properties will provide the best results. The need to create new materials that have a set of superior properties has become critical due to the high demand on the manufacturing industry for effective use of natural resources. Although some materials can attain some desirable characteristics, there was a great limitation imposed upon them because of their limited availability and relatively low strength-to-weight ratios.[1]. Composite material is any type of material whose improved properties have been created by mixing or bonding two or more different materials that have very different physical or chemical properties. This mixture forms a new material that remains to be special in its own ways, which cannot be identified as to its components. This is an increase that would make the composite material better than the individual materials [2]. The innovation involving composite materials hinges on how one can arrive at the best base metal and combinations with appropriate reinforcements [3]. The reinforcement, may have the form of fibres, whiskers, or particulates of natural or synthetic material [4]. The type, size,

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and percentage of addition, followed by the uniformity of their dispersion and the generated interfacial integrity of the matrix-reinforcement particles along with the grain refinement, are all important reinforcement characteristics that contribute to the improvement of good mechanical and tribological properties of the composites [5]. It helps assess the material's wear resistance, friction coefficient, and surface characteristics under sliding conditions [6]. RF, GB and k-NN, SVR and ANN are regarded as to predict wear rate and coefficient of friction with the help of the Machine Learning Algorithms. The performance metrics such as MSE, RMSE and MAE were used to estimate the performance of the ML models.

II. LITERATURE REVIEW

As was established by S V Alagarsamy et al., maximum weight of TiO2 ceramic reinforcement in Al7075 aluminium matrix alloy gave acceptable particle dispersion and past this weight, the element was likely to create agglomerations because of segregations and particle rejection leading to the formation of agglomerations. To enable the inclusion of a higher part of the weight of ceramic reinforcement, they suggested that the stirring time

Shirvani Moghaddam et al., suggest the optimal percentage of reinforcement to be used to achieve the highest strength and they discovered that increasing the percentage of reinforcement beyond the optimum values led to reduced strength. In the case where the composite material comprised of the agglomeration of particles and the presence of interaction of porosity, the resistance to flowability adversely affected the ductility of the composite too

J. M. Mistry et al., researched on Al7075 particle-reinforced with Si3N4 particles, prepared by the electromagnetic stir casting method, finds out that results save tremendous mechanical and tribological properties. The hardness and tensile and flexural strengths reach their maximum values with 8 wt.% and 360 °C of reinforcement addition, respectively, and decrease at 12 wt% and 360 °C,respectively . Kalyon et al., Investigated the wear loss of the SiC reinforced Aluminum composites. To predict the wear loss of the composites an artificial neural network (ANN) model is used. While predicting the wear loss 85% of experimental data was used for training and 15% of data was used for testing. They were able to find a value of R2= 0.9855 when comparing with experimental weight loss.

Shyam Hasan et al., Compiled experimental data points of Al/Graphite composites of wear rate and coefficient of friction of different researchers to validate the experimental data, with the help of installation of Machine Learning (ML) models. The performance metrics such as MSE, RMSE and MAE were used to estimate the performance of the ML models. The results showed that the Random Forest algorithm performed well in the prediction of wear rate and gradient boosting performed well in prediction of coefficient of friction.

III. MATERIALS AND METHODS

MATERIALS

The composites to be used in this study are worked out through the considerations of the Al7075 and the Si3N4 as the matrix and the reinforcement respectively. Si3N4 is less chemically reactive with aluminum and more thermal shock resistant than the carbide and oxide reinforcements; a property that provides interfacial stability and consistent frictional behavior. Hence, these properties make Si_3N_4 particularly suitable for tribological applications. One of the desirable conditions to the successful production of the Al7075/Si3N4 composites is the difference in density of the matrix and the reinforcement phases.

Fig. 3.1 Al7075 Alloy ingots

Fig. 3.2 Si3N4 particles

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Table 3.3 Composition of weight % of Si3N4 in Al7075 Al

S.No.	Al7075 Alloy (%)	Si3N4(%)
1	100	0
2	97	3
3	94	6
4	91	9
5	88	12
6	85	15

Fig. 3.5 Fabricated components through stir casting

TABLE 3.7 PROCESS PARAMETERS AND THEIR LEVELS FOR WEAR TESTING

S. No.	Process parameters	Value
1.	Reinforcement (wt.%)	0, 3, 6, 9, 12
2.	Load (N)	10, 20, 30
3.	Sliding Velocity(m/s)	1.5, 2.5, 3.5
4.	Sliding distance (m)	1500

IV. RESULTS AND DISCUSSIONS

4.1 Mechanical properties (Hardness, Tensile, Tribological, Wear rate and Coefficient Friction)

4.1.1 Hardness

Si3N4 weight in Al7075alloy	Hardness (BHN)	Percentage of enhancement of hardness
0	75.2	-
3	96.44	28.24
6	104.56	39.04
9	115.2	53.19
12	118	56.91
15	111	47.6

Table 4.1 Hardness and Percentage of enhancement of hardness

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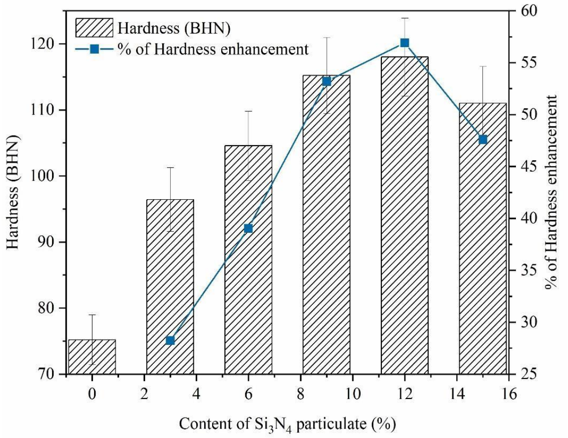

Fig. 4.4 Hardness enhancement with the weight fraction of Si3N4 Reinforcement

4.2Tensile properties

The fractured tensile specimens are shown in Fig. 4.5. The Table 4.2 indicated the tensile strength, percent elongation after testing and the yield strength.

Fig. 4.5 Fractured Tensile testing specimens

Si3N4 weight % in Al7075alloy	Ultimate tensile strength (MPa)	Yield strength (MPa)	Percentage of elongation
0	215	148	9.3
3	223	159	5.7
6	248	172	3.6
9	272	178	2.8
12	281	152	1.6
15	268	174	2.5

Table 4.2 Tensile strength, Yield strength and percentage of elongation

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4.3 Tribological properties

The wear tests were conducted on pin on disc apparatus at different load and sliding velocities for the produced composites at 1500m sliding distance. The details of process parameters and their levels for wear testing are given in Table 4.3. The wear rate and COF values at different process parameters are shown in Table 4.4.

S. No.	Process parameters	Value
1.	Reinforcement (wt.%)	0, 3, 6, 9, 12
2.	Load (N)	10, 20, 30
3.	Sliding Velocity(m/s)	1.5, 2.5, 3.5
4.	Sliding distance (m)	1500

Table 4.3 Process parameters and their levels for wear testing

S.No.	Si_3N_4Weight (%)	Load (N)	Sliding Velocity (m/s)	Wear rate(mm^3/m)	Coefficient of friction(μ)
1	0	10	1.5	0.00550	0.56217
2	0	10	2.5	0.00975	0.53875
3	0	10	3.5	0.01149	0.52127
4	0	20	1.5	0.00806	0.53146
5	0	20	2.5	0.01231	0.49893
6	0	20	3.5	0.01383	0.48567
7	0	30	1.5	0.01333	0.4904
8	0	30	2.5	0.01764	0.45303
9	0	30	3.5	0.01854	0.41675
10	3	10	1.5	0.00325	0.49769
11	3	10	2.5	0.00767	0.49603
12	3	10	3.5	0.00844	0.49319
13	3	20	1.5	0.00581	0.49076
14	3	20	2.5	0.00961	0.46965
15	3	20	3.5	0.01235	0.44452
16	3	30	1.5	0.01077	0.43134
17	3	30	2.5	0.01618	0.39213
18	3	30	3.5	0.01766	0.33418
19	6	10	1.5	0.00204	0.42279

Table 4. 4 Wear rate and coefficient of friction at different process parameters

The composites wear rate under high load and high sliding velocity conditions ranging between 3% to 12% increased Si3N4 ceramic particulate content is 0.0176, 0.0152, 0.0134 and 0.0118 respectively whereas the average COF of the composites is 0.33, 0.31, 0.26 and 0 The increased load and sliding has significantly increased the wear rate along with reduced COF. The wear resistance capability of the composites was enhanced with the introduction of Si3N4 particulate content and also the COF was reduced as well

V. PREDICTION OF TRIBOLOGICAL CHARACTERISTICS USING MACHINE LEARNING ALGORITHMS

S.No.	Si_3N_4 weight (%)	Load (N)	Sliding Velocity(m/s)	Wear Rate (mm^3/m)	COF (μ)
1	0	10	1.5	0.00412	0.55379
2	0	10	2.5	0.00613	0.54497
3	0	10	3.5	0.00778	0.53485
4	0	10	1.5	0.00529	0.54202

5	0	10	2.5	0.00938	0.52771
6	0	10	3.5	0.01105	0.52311
7	0	10	1.5	0.0055	0.56217
8	0	10	2.5	0.00975	0.53875
9	0	10	3.5	0.01149	0.52127
10	0	20	1.5	0.00708	0.54321
11	0	20	2.5	0.01015	0.49975
12	0	20	3.5	0.01219	0.47973
13	0	20	1.5	0.00793	0.53882
14	0	20	2.5	0.01203	0.49517
15	0	20	3.5	0.01351	0.48856
16	0	20	1.5	0.00806	0.53146
17	0	20	2.5	0.01231	0.49893
18	0	20	3.5	0.01383	0.48567
19	0	30	1.5	0.00803	0.48998
20	0	30	2.5	0.01106	0.44157
21	0	30	3.5	0.01413	0.43627
22	0	30	1.5	0.00918	0.49875
23	0	30	2.5	0.01381	0.46505
24	0	30	3.5	0.01416	0.4361
25	0	30	1.5	0.01333	0.4904
26	0	30	2.5	0.01764	0.45303
27	0	30	3.5	0.01854	0.41675

Table 5.2 Wear rate and coefficient of friction at different process parameters

ML Model	MAE	MSE	RMSE	MAPE	R2 Value
RF	0.1915	0.0494	0.2223	7.90%	0.9506
GB	0.1789	0.0471	0.2170	4.84%	0.9529
X`k-NN	0.3133	0.1305	0.3612	16.29%	0.8695
SVR	0.1498	0.0314	0.1772	9.26%	0.9686
ANN	0.2353	0.0889	0.2982	17.96%	0.9111

Table 5.2 Performance matrices for wear rate

ML Model	Testing	Training
RF	0.9506	0.9904
GB	0.9529	0.9982
k-NN	0.8695	0.9526
SVR	0.9686	0.9778
ANN	0.9111	0.9136

Table 5.3 Comparison of Testing and Training R^2 values for wear rate

VI. CONCLUSIONS

1.(a)The composites are fabricated through a stir-casting approach for varied reinforcement content in the Al7075 matrix from 0 to 15% (i.e.,0%, 3%, 6%, 9%, and 15 wt.%).

(b) The grain enhancement is primarily explained by the nucleation of aluminium matrix grains and restricted grain growth due to the presence of Si3N4 particulate distribution during solidification.

(c) SEM images confirm the uniform dispersion of Si3N4 particulate with considerably fewer particle agglomerations throughout the Al7075 matrix alloy.

(d) The SEM and EDS analysis showed good integrity at the matrix-refinement interface with no interfacial compound formation.

2. The enhancement of mechanical properties such as hardness up to 118BHN, tensile strength, and yield strength up to 281 MPa and 178 MPa, which are 30.69% and 20.27% strength enhancement respectively. The reduced percentage elongation (ductility) of the composites due to the reinforcement of Si3N4 particles is attributed to the creation of increased crack initiation sites.

3. (a)The average wear rate of the composites is 0.019, 0.0085, 0.0075, and 0.0065 respectively for the increased Si3N4 ceramic particulate content from 3% to 12%, while the average COF of the composites is 0.45, 0.37,0.32 and 0.28, respectively for the increased Si3N4 ceramic particles content from 3% to 12% within the region of selection of the tribological conditions like load and sliding velocity.

(b) The increased load has significantly increased the wear rate along with reduced COF. With the addition of Si3N4 particulate content, the wear resistance performance of the composites at 30N has shown up to 46% enhancement for varying Si3N4 particulate content from 3 to 12%wt., while reducing the COF up to 65%.

4.The R^2 values for all five machine learning models of RF, GB, k-NN, SVR, and ANN are 0.9177, 0.9051, 0.8409, 0.9475 and 0.9429 respectively; MAE values are 0.2403, 0.2511, 0.3355, 0.1742, and 0.1867, respectively; MSE values are 0.0822, 0.0949, 0.1591, 0.0524, and 0.0570, respectively; and RMSE values are 0. 0.2868, 0.3081, 0.3989, 0.2290, and 0.2388, respectively. From the above results, the support vector regression performed well with a high R2 value of 0.9475 and a low MAE value of 0.1742, MSE value of 0.1591, and RMSE value of 0.3989 while predicting the COF.

V. ACKNOWLEDGMENT

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