Heat Treatment Parameters to Optimize Friction and Wear behavior of Novel Hybrid Aluminium Composites Using Taguchi Technique

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Abstract- In the present study, an Al 7075 alloy is used as the matrix and varying weight percentage of Silicon Carbide (SiC) and constant weight percentage of Boron Carbide (B_4C) as the reinforcing material. The composite is produced using stir casting technique. The composite thus formed is termed as hybrid composite. The samples are prepared for heat treatment process by subjecting to solutionizing temperature of 530°C for 1 hr followed by quenching in water. Further the specimens are subjected to artificial aging for durations of 4, 6 and 8 hr at a temperature of 175°C. The mechanical and tribological properties of composites before and after heat treatment are examined by Vickers hardness test machine and pin-on-disc test machine respectively. The wear rate and friction co-efficient of heat treatment parameters are evaluated based on Taguchi technique. The analysis is further extended to the optimization of test parameters using Design of Experiment (DoE) based on L9 orthogonal array. The developed Analysis of Variance (ANOVA) and the regression equations is obtained through MINITAB R16 are used to investigate the influence of parameters like sliding speed, applied load, sliding time, and percentage of reinforcement on the dry sliding wear and friction co-efficient of the composites. The wear surface morphology and wear mechanism of the pins are investigated using Scanning Electron Microscope (SEM) and are correlated them with wear test results. Finally, confirmation tests are carried out to verify the experimental results.

Keywords: Hybrid Composite, Solutionizing, Aging, Dry Sliding Wear, Taguchi Technique, Orthogonal Array, Analysis of Variance.

I. INTRODUCTION

In the recent development, metal matrix composites congregate to meet the increasing overall demand for light weight, high performance, eco-friendly, wear, and corrosion resistant materials. The Hybrid Aluminium Metal Matrix Composites (HAMMCs) are in advance extensively used in some areas due to its enhanced mechanical properties (and lighter density) when compared with metals/alloys, particularly in applications where weight and strength are of most important consequence. The advantages of particulate-reinforced composites over others are their formability with expenditure benefit and its different strengthening mechanisms [1, 2]. The HAMMCs are suitable for appliances which oblige characteristics such as combined strength, damping properties thermal conductivity, and co-efficient of thermal expansion along with lesser density. The unique properties of HAMMCs enhance their usage in automotive and tribological applications such as in pistons, brake drum, brake disc and cylinder block etc. [3-5].

In casting process, the reinforcing elements such as metal carbides, metal borides, metal nitrides and metal oxides are dispersed within molten alloy matrix under atmospheric pressure. Recently, liquid processing method is developed to make MMCs with higher volume fraction of reinforcement under much lower pressure [6]. The modern research studies reported that the homogeneous mixing can be obtained by selecting appropriate processing parameters like stirring speed, time and temperature of the molten metal, preheating temperature of the mould and uniform feed rate of the particles [7, 8].

The main focus of the selection of suitable process engineering depends on the desired kind, quantity and distribution of the reinforcement components, the matrix alloy and its application. Among the various aluminium alloys, 7075 is quite popular choice as a matrix material to prepare metal matrix composites owing to its better formability characteristics and the option of modification of the strength of composites through heat treatment [9-12]. The addition of SiC particles into the aluminium matrix improves the wear resistance due to the hardness of the particles [13]. In particulate reinforced HAMMCs, reinforcement is added to the matrix of the bulk material to increase its stiffness and strength [14-16]. The addition of hard ceramic particles like SiC, Al_2O_3, and B_4C etc., results in enhanced wear resistance and strength to weight ratio than the conventional alloys [17, 18]. Achievement of these properties depends upon primarily on the selection of reinforcement, its method of production and chemical compatibility with the matrix.

In engineering materials system, the heat treatment processes are incredibly essential for improving the composite material properties. The main purpose of heat treatment is to create the material system structurally and physically strong and fit for engineering application [19]. Heat treatment of aluminium alloys favors the maximum concentration of hardening solute to dissolve into solution. This method is suspiciously conceded out by heat treatment of an alloy to a temperature at which one single, solid phase exists. By this heat treatment, the solute atoms that are originally part of a two phase solid dissolve into solution and originates (create) as one single phase. Once the alloy is heated to the recommended solutionizing temperature, it is quenched at a rapid rate such that the solute atoms don't have enough time to precipitate out of the solution. As a result of the quench, a super saturated solution now exists between solute and aluminium matrix [20, 21].

Rapid quenching creates a saturated solution resulting in increased hardness and mechanical properties of the material system. In addition to these studies, the highest degree of corrosion resistance is obtained through maximum rates of quenching [22]. Quenching takes place in three distinct stages namely vapour blanket stage, boiling stage and liquid cooling stage. The vapour blanket stage begins when hot part submerged in unbroken blanket which surrounds the object. This blanket exists between the specimen and quenching media if the heat from the surface of the object exceeds the amount of heat needed to form maximum vapour per unit area of the object.

A numerical analysis of pin on disc tests on Al-Li/SiC composites at different loads and temperature [23]. The tribological properties such as wear rate and friction co-efficient are considered to be one of the major factors controlling the performance of any HMMC. The tribological properties of the reinforced aluminium matrix composite prepared by vortex method with short steel fibers [24]. The wear rate and friction co-efficient are determined by using pin-on-disc type apparatus by varying the applied load from 10-40 N with a constant sliding velocity of 1.8 m/s and a sliding distance of 2000 m and concluded that the volumetric wear increases with increasing applied load and the transition from mild wear to severe wear depends on the strength of the pin material adjacent to the surface. All these factors on the whole created tremendous development in the research field worldwide in manufacturing HAMMCs with improved physical, mechanical and tribological properties [25, 26].

An experiment is designed to evaluate simultaneously two or more factors which possess their ability to affect the resultant average or variability of particular product or process characteristics. The design of experiment should focus on preferred level of influencing factors. The results of the particular test combinations are observed and the complete sets of results are analyzed to determine the preferred level of the various influencing factors [27]. Taguchi technique is an optimization tool for solving the design problems. [28]. This method significantly reduces the number of experiments that are required to model the response function compared with the full factorial design of experiments. Moreover, it is a systematic and easy approach to optimize the design parameters such as quality and cost [29]. It is a multi-step process technique to find the possible interaction between the parameters. This approach is a factorial design approach and creates a standard orthogonal array [30].

Based on the Taguchi technique, an orthogonal array is used to reduce the number of experiments for finding out optimum test parameters as established. Investigation of the experimental outcomes uses SN to support the determination of the finest process design and has effectively been used for the study of dry sliding wear behavior of composites materials [31]. The identified influencing parameters on the wear rate and friction co-efficient are applied load, sliding velocity, sliding time and percentage of reinforcement.

Most of the research work is reported on Al 7075 with different reinforcement such as silicon carbide, silicon, boron carbide, titanium, alumina etc. But none of them had attempt for Al 7075 with two types of reinforcements like SiC and B_4C. From the above discussion it is concluded that no enough data is available on the mechanical properties and wear resistance of heat treated two particulate reinforced matrix alloys of Al 7075. Hence, the present study is aimed to fabricate treated Al7075/SiC/B_4C composites with varying weight percentage of particulates reinforcement and to study their microstructure, micro-hardness, mechanical, tribological properties and thermal analysis with application of the brake drum.

An optimization technique namely Taguchi design of experiments is also been selected for the above combination of work, to investigate the effect of parameters such as applied load, sliding velocity and sliding distance on dry sliding wear behavior of the Al 7075/SiC/B_4C composites. Considering the above facts, an attempt is made to employ ANOVA to find the percentage of influence of various factors and its interaction on dry sliding wear of the composites.

II. MATERIALS SELECTION

The nominal chemical composition of Al 7075 alloy is given in Table I. This matrix alloy is preferred as it provides exceptional combination of strength to weight ratio and damage tolerance at elevated and cryogenic temperatures. The density measurements are all set according to the ASTM standard C1270-88. The values of hardness and density for matrix materials are 160 VHN and 2.76 g/cm^3 respectively in tempered condition. Hardness of the specimens is measured using Vickers hardness tester by applying a load of 10kg and the average value of hardness from 10 different data of the experiments is considered.

TABLE I Composition of Al 7075 By Weight Percentage

Elements	Si	Fe	Cu	Mn	Ni	Zn	Ti	Mg	Cr	Al
% by weight	0.06	0.18	1.63	0.074	0.05	5.62	0.049	2.52	0.22	Balance

III. PREPARATION OF THE COMPOSITE AND TESTING

The stir-cast technique set up as shown in Fig.1 is used to prepare composite specimens [32]. In this process, matrix alloy (Al 7075) is firstly superheated over its melting temperature and then temperature is gradually below the liquids temperature to keep the matrix alloy in the semi-solid state. At this temperature, the preheated of varying weight percentage SiC (5%, 10% and15%) and constant weight percentage B_4C (3%) in addition to 1% magnesium (Mg) particles are introduced into the slurry and mixed. The composite slurry temperature is increased to fully liquid state and automatic stirring is continued for 10 min at an average stirring speed of 500 rpm. The melt is then superheated above liquids temperature and finally poured into the cast iron permanent mould as per required dimensions. The test specimens are machined to obtain cylindrical pins having a diameter of 8, 10 and 12 mm and height of 32 mm. The specimen faces are metallographically polished. The cast composites are subjected to solutionising at a temperature of 530°C for 1 hr followed by quenching using water. The quenched samples are then subjected to artificial aging for different durations of 4, 6, 8 hr at a temperature of 175^o C.

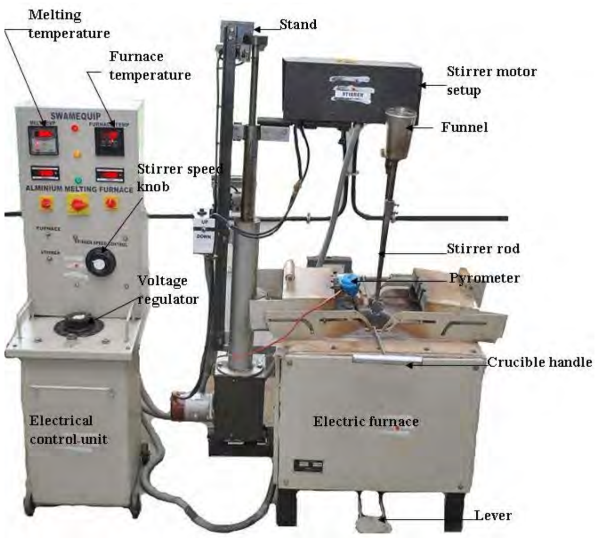

Fig.1The experimental set up used in fabrication of HAMMCs (Al 7075/SiC/B_4C)

The specimens are age hardened and the Vickers hardness values for different conditions as per ASTM standard tested as mentioned in Fig.2. The Solutionizing temperature and duration of 530^{o}C and 1 hr respectively is adopted and quenched in water media. At a temperature of 175^{o}C with different duration of time the samples are heated and cooled naturally. Quenching and aging significantly alters the micro-hardness of both the Al 7075 matrix alloy and its composites. From Fig. 2 the results is obtaining maximum hardness is observed for both the Al 7075 alloy matrix and reinforced composites.

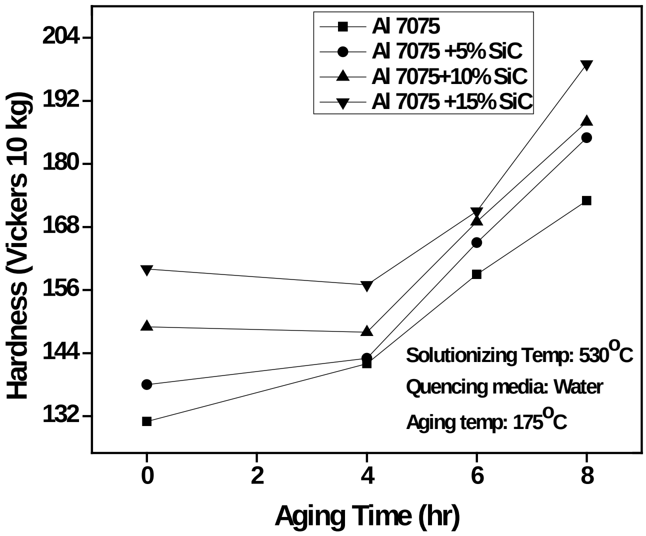

Fig. 2 Variation of hardness with increase in wt % of reinforcement for as cast Al 7075matrix alloy and Al 7075 particulates composites

IV. WEAR TEST EXPERIMENTAL SETUP AND PROCEDURE

A pin-on-disc wear test experimental setup is used to investigate the dry sliding wear characteristics of the composite. The slider disc is made up of 0.95 to 1.20% carbon (EN31) hardened steel disc with hardness of 62 HRC having a diameter of 165 mm. A track diameter of 100 mm is used in all the experiments. The initial surface finish (Ra) of the steel disc is 1μm. The heat treated Hybrid Aluminium Metal Matrix Composite (HAMMC) samples are prepared as pins of dimensions 12 mm in diameter and 32 mm in height. It is important to ensure that the test sample's end surfaces are flat and are polished by using metallographic techniques prior to wear testing. Conventional aluminium alloy polishing techniques are used to make the contact surfaces of the monolithic composite aluminium specimen ready for wear test.

The tests are carried out by applying normal loads such as 10, 20 and 40N at a maximum sliding distance of 4241m at different velocities such as 1.5, 3.0 and 4.5 m/s. The wear rates of test samples are measured in weight units by weighing the specimen before and after the test and are finally converted into volumetric wear loss. The wear losses of the specimens are measured using a high precision (accuracy 0.001g) electronic balance. The difference in weight loss of the entire test samples are measured before and after the wear test under dry condition. Using this weight loss data, the composite's weight loss is calculated. At last, the micro structural investigation and semi quantitative chemical analysis on the worn surfaces are performed by SEM.

The specimens are tested as per the procedure reported in papers [33- 35]. The experiments are conducted as per the standard L9 orthogonal array. The measured results are analyzed using the commercial software MINITAB 16 specifically used for design of experiment applications. The wear parameters selected for the experiment are sliding speed, applied load, sliding time, and percentage of reinforcement [36]. The each parameter is assigned three levels which are shown in Table II. The standard L9 orthogonal array consists of nine tests as shown in the Table III. The first column is assigned by sliding speed, second column is assigned by applied load, third column is assigned by sliding time and fourth column is assigned by percentage of reinforcement. The response to be studied is the wear with the objective as smaller, as the better. The sliding wear test results are subject to the analysis of variance.

Table II Process Parameters and Levels

Level	Speed S (m/s)	Load L (N)	Time t (min)	Reinforcement R (%)
1	1.5	10	5	5
2	3	20	10	10
3	4.5	40	15	15

Table III Orthogonal Array L9 of Taguchi Method

Ex. No	Speed (m/s) S	Load (N) L	Time (min) t	Reinforcement (%) R	Wear Rate mm^3/m Wr	S/N Ratio for Wear (db)	Co-efficient of Friction Cof	S/N Ratio for Co-efficient of Friction (db)
1	1.5	10	5	5	0.100070	19.993922	0.4211	7.5122951
2	1.5	20	10	10	0.100150	19.986980	0.3979	8.0045212
3	1.5	40	15	15	0.097830	20.190558	0.3489	9.1459806
4	3	10	10	15	0.011100	39.093540	0.3001	10.454680
5	3	20	15	5	0.076510	22.325635	0.3673	8.6995814
6	3	40	5	10	0.079963	21.942218	0.3389	9.3985686
7	4.5	10	15	10	0.023410	32.611971	0.3101	10.169964
8	4.5	20	5	15	0.002032	53.841525	0.3117	10.125263
9	4.5	40	10	5	0.019622	34.145134	0.3779	8.4524621

V. RESULTS AND DISCUSSIONS

The influence of controlled process parameters such as sliding speed, applied load, sliding time and percentage of reinforcement is analyzed and the rank of involved factors like wear rate and co-efficient of friction which supports Signal to Noise Response (SN) is given in Tables IV and V.

TABLE IV Response Table for SN Ratio- Smaller is better (Wear Rate)

Level	Speed (m/s)	Load L (N)	Time t (min)	Reinforcement (%) R
1	20.06	26.57	31.93	25.49
2	27.79	32.05	31.08	24.85
3	40.20	37.43	25.04	34.71
Delta	20.14	10.86	6.88	9.22
Rank	1	2	4	3

TABLE V Response Table for SN Ratio- Smaller is better (Friction Co-efficient)

Level	Speed S (m/s)	Load L (N)	Time t (min)	Reinforcement R (%)
1	8.221	9.379	9.012	8.221
2	9.518	8.943	8.971	9.191
3	9.583	8.999	9.339	9.909
Delta	1.362	0.436	0.368	1.687
Rank	2	3	4	1

VI. ANALYSIS OF VARIANCE (ANOVA) FOR WEAR RATE

The Analysis of Variance (ANOVA) is used to analyze on the wear rate for SiC and B_4C particulates reinforced Al 7075 alloy matrix composite as given in Table VI. This analysis is carried out at a level of 5% significance that is up to a confidence level of 95%. From Table VI, one can easily observe that the sliding speed factor is greater influence on wear rate (46.8231%). Hence, the sliding speed is an important control process parameter to be taken into account while wear process. Sliding speed is further followed by applied load

(32.6391%), Percentage of reinforcement (17.6178%). From Table VII, one can clearly infer that the percentage of reinforcement factor is greater control on co-efficient of friction (40.8665%) than the other factors. Hence added percentage of reinforcement is an important parameter to be taken into account while considering co-efficient of friction. This parameter is then followed by sliding speed (31.5033%), applied load (27.0864%), and sliding time (0.69183%).

TABLE VI Analysis of Variance for Wear Rate (mm^3/m)

Source	DF	Seq SS	Adj SS	Adj MSS	F-test	P-Value	Pr%
S (m/sec)	2	0.004422189	0.004422189	0.0053353	8.27	0.038	46.8231
L (N)	2	0.003802173	0.003802173	0.0003469	0.54	0.621	32.6391
t (Min)	2	0.000057365	0.000057365	0.0008826	0.31	0.749	2.9285
R (%)	2	0.000971142	0.000971142	0.0004077	0.14	0.871	17.6178
Error	0	0.014057986	0.014057986				0
Total	8	0.014158695					100

TABLE VII Analysis of Variance for friction co-efficient

Source	DF	Seq SS	Adj SS	Adj MSS	F-test	P-Value	Pr%
S (m/sec)	2	0.004422189	0.004422189	0.0030250	1.59	0.310	31.5033
L (N)	2	0.003802173	0.003802173	0.0001882	0.10	0.908	27.0864
t (min)	2	9.71148E-05	9.71148E-05	0.0002522	0.16	00.860	0.69183
R (%)	2	0.005736508	0.005736508	0.0035532	2.21	0.226	40.8665
Error	0	0.014057986	0.014057986				0
Total	8	0.014037182					100

VII. MULTIPLE LINEAR REGRESSION MODELS

A multiple linear regression equation is used to develop the relationship between independent predictor variable. This developed and a response variable by fitting a linear equation to the measured data. The regression wear rate and friction co-efficient of the model is 0.896 and 0.871 respectively.

The equation obtained is as follows,

$$\mathrm{Wr} = 0.149 - 0.0281\mathrm{S} + 0.000643\mathrm{L} + 0.00052\mathrm{t} - 0.00284\mathrm{R} \qquad ----\mathrm{Eqn}\ (1)$$

$$\mathrm{Cof} = 0.485 - 0.0187\mathrm{S} + 0.000301\mathrm{L} - 0.00151\mathrm{t} - 0.00685\mathrm{R} \qquad ----\mathrm{Eqn}\ (2)$$

VIII. SCANNING ELECTRON MICROSCOPE EXAMINATION

Fig. 3 (a-d) shows the worn surfaces micrographs of heat treated reinforced and unreinforced samples. The surfaces is examined by SEM and wear rate depends on the presence of carbide phase in matrix. All through sliding, the entire surface of the pin is contact with the surface of the steel disc and machine marks can also be observed. The parameters for this surface decided such as applied load of 40N, sliding speed of 4.5m/s, percentage of reinforcement of 15% and sliding time 15min respectively. Grooves are mainly formed by the reinforcing particles. As the sliding speed increases, the number of grooves also increases and the reinforcements are projecting out from the pin surface due to ploughing action between counterface and pin and formation of wear debris is also observed. The ceramic particles are found inside the cavities and some particle are broken where as the other particle are pulled out from the surface.

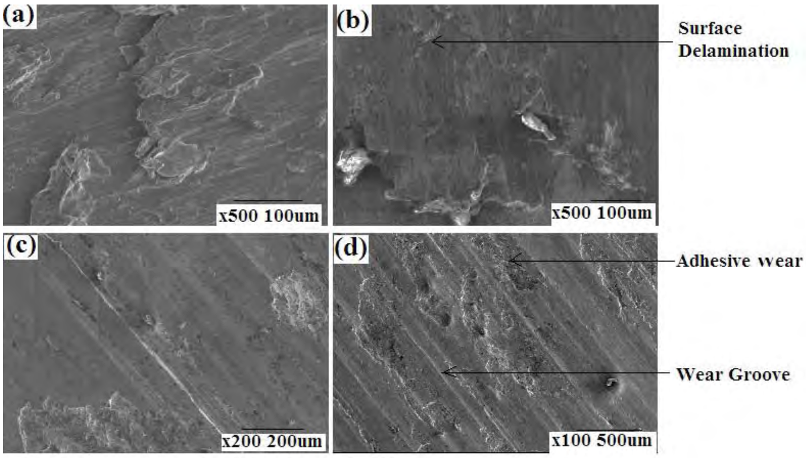

Fig 3. SEM Photographs of the treated worn surfaces of a) Al 7075 alloy.
b) Al 7075/5%SiC/3%B_4C. c) Al 7075/10%SiC/3%B_4C and d) Al 7075/15%SiC/3%B_4C.

IX. CONFIRMATION EXPERIMENT

The final step process is confirmation test and performed for composite materials by selecting the set of parameters as shown Table VIII. The input task is the determination of the preferred combination of the levels of the parameters indicated to be significant by the analytical methods and also to validate the conclusions drawn during the analysis phase. The experimental value of wear rate and friction co-efficient of both the results are compared and observed that the calculated error varies from 2.12% to 8.74% and 4.01% to 9.82% respectively are shown in Table IX. Thus, the calculated wear rate and co-efficient of friction from the regression equation and experimental values are nearly same with least error.

TABLE VIII Confirmation Experiment for Wear Rate and Co-efficient of Friction

Level	Speed S (m/s)	Load L (N)	Time t (min)	Reinforcement R (%)
1	1.9	15	4	5
2	3.2	25	8	10
3	4.3	35	12	15

TABLE IX Result of Confirmation experiment and their comparison with Regression model

Exp. No	Exp. Wear Rate (mm^3/m)	Reg. model equ(1), Wear Rate(mm^3/m)	% Error	Exp. Co-efficient of friction	Reg. model equ(2), co-efficient of friction	% Error
1	0.130855	0.125065	4.63	0.43878	0.412545	6.36
2	0.049628	0.049025	2.12	0.36341	0.349385	4.01
3	0.018622	0.017125	8.74	0.32522	0.296125	9.82

X. CONCLUSIONS

Using the Taguchi technique to find out the optimum parameters for wear rate and friction co-efficient of the composites, the following conclusions can be drawn from the study.

1. The stir-cast experimental set up could be successfully adopted in the preparation of Al 7075/SiC/B_4C composites.
2. DoE by Taguchi technique and regression equation is successfully used to study the dry sliding wear rate and friction co-efficient of composites.
3. The wear rate and friction co-efficient are dominated by different parameters in the order of applied load, sliding speed, percentage of reinforcement, and sliding time.

4. 4.5m/s sliding speed, 10N applied load, 15min sliding time, and 15% of reinforcement are the optimum conditions for both wear rate and the co-efficient of friction.
5. Sliding speed (46.823%) is the highest influence on wear rate followed by applied load (32.6391%) and percentage of reinforcement (17.6178%) and for co-efficient of friction, the contribution of sliding speed (31.5033%), applied load (27.0864%), and percentage of reinforcement (40.8665%).
6. The percentage of pooled error is carried out by confirmation tests with wear rate ranges between 2.12% to 8.74% and between 4.01% and 9.82% for co-efficient of friction, resulting in the conclusion that the design of experiments by the Taguchi method is successful for calculating wear rate and co-efficient of friction from the regression equation.
7. Finally, the multiple regression values obtained for wear rate and co-efficient of friction are 0.896 and 0.871 respectively.

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