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RESEARCH

Effect of Heat Treatment on the Wear Behaviour of Functionally Graded LM13/B_4C Composite

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A B S T R A C T

Aluminium alloy reinforced with boron carbide (10 wt.%) was fabricated using stir casting method followed by centrifugal casting and the cylindrical specimen with dimension 150 x 150 x 15 mm was obtained. The composite specimens were heat treated at various aging temperatures and aging time for property improvement. Solution treatment was done at 525 °C for 5 hrs. Taguchi's method was used for designing the plan of experiments and L27 orthogonal array was formulated for the analysis of data. The wear test was conducted on the outer periphery of centrifugally cast Functionally Graded composites using pin-on-disc tribometer. Optimization of parameters such as applied load (10 N, 20 N, 30 N), agingtemperature (150 °C, 175 °C, 200 °C) and aging time (2 hrs, 6 hrs, 10 hrs) was done using Signal-to-Noise ratio. "Smaller-the-better" criterion was used for analyzing the results. Results ended up with a conclusion that aging time (92.19 %) had major influence on tribological behavior followed by aging temperature (5.36 %) and applied load (1.95 %). Scanning Electron Microscope (SEM) analysis was performed to understand the wear mechanism in heat treated specimens.

1. INTRODUCTION

The Aluminium Metal Matrix Composites (AMMCs) are bringing momentum in the research area from the last two decades because of environmental friendliness and high performance [1]. The metal matrix composites (MMCs) have a wide range of applications in various fields because of the high strength to weight ratio, thermal resistance and damping properties [2]. Because of light weight, corrosion and wear resistance, AMMCs are used for manufacturing fan blades in turbines, clutches, brake linings, piston, brake drum and cylinder block [3]. MMCs are the engineering materials which can achieve better mechanical properties by reinforcing high stiffness and high strength material in a soft metal matrix. The AMMCs has growth in automobile industries because of durability and good surface finish [4]. Research is going in improving the properties of aluminium MMCs by using different reinforcement to get high efficiency [5]. Manufacturing techniques like stir casting, squeeze casting, liquid metal infiltration and spray co deposition are available [6]. However manufacturing of a MMC has various problems like poor wettability, porosity and improper distribution of reinforcement. So, proper care is taken in choosing the manufacturing method. In order to avoid non uniformity, stir casting technique is used [7]. The homogenous property of material has a wide range of applications where the property is required throughout the body like furnace, mechanical structures, chasis and cross members. Some applications like piston head, liner and brake drum need higher wear resistance on the periphery, as the surface is the only part where better tribological properties are required. In order to obtain these peripheral better properties, Functionally Graded Material (FGM) is chosen. FGM are first proposed by Japanese, and later these materials became a new brand of composite materials. FGM improves the peripheral strength by incorporating the reinforcement concentration on the outer surface. One unique characteristic of FGM is ability to tailor for specific application [8]. The heat treatment will enhance the surface properties of the materials. The main purpose of heat treatment is to make the material suitable for engineering application [9]. Solution treatment of aluminium alloys helps in obtaining maximum concentration of solute to get dissolved. Without heat treatment the solute and solvent exits in two different phases. Once the heat treatment is done the solute got dissolved into solvent and a single phase is formed. As the formation of phase depends on aging time and temperature, investigators stated that these two parameters have a lot of influence on the wear properties of the AMMC's [10,11].

Adhesive wear is caused when there is relative motion between two surfaces in which material is transferred from one surface to another because of solid phase welding or a localized bonding between the surfaces [12]. Adhesive wear occurs when the pressure applied is such that there is a possibility of occurrence of plastic deformation [13]. The major factors influencing in the wear behavior of a MMC are reinforcement particle size, inter particle spacing and bond strength [14]. Reinforcements like Silicon Carbide (SiC), Titanium Carbide (TiC) and Boron Carbide (B_4C) are used in composite preparation. Among these reinforcements, considering the above parameters, it is stated that B_4C has better wear properties [15]. Design of experiments (DOE) is done using Taguchi method formulated by Taguchi and konishi [16]. This is the most common method used by engineers to optimize the effect of parameters on the engineering problems [17,18].The orthogonal array used to execute the experiments and analyze the results of the experiment in a Taguchi method.

1.1 Material Selection

An attempt is made to analyze the wear behavior of heat treated functionally graded Al LM13/B_4C (10 wt.%, 25 μm) composite. Among the aluminium alloys, LM13 is more preferred for preparing MMC's for automobile and tribological applications due to its good adhesive wear properties. Research shows that wear properties can be enhanced by reinforcing ceramic materials in LM13. B_4C is more preferred because of its high strength and extremely high hardness as well as toughness. It has low density of 2.47 g/cc which shows better wettability when mixed with the LM13 alloy which is having a density of 2.7g/cc. The composition of the base alloy is shown in the Table 1.

Table 1. Chemical Composition of Al LM13 alloy.

Chemical composition	Al	Si	Fe	Cu	Mg	Ni	Other
wt.%	83.4	10.9	0.53	1.31	1.05	2.32	0.49

2. EXPERIMENTAL METHODOLOGY

To understand the wear properties of a FGM, the following methodology is used. The composite is fabricated and prepared specimens are subjected to heat treatment. The wear test is conducted on the heat treated specimens.

2.1 Fabrication of Material

Fabrication of the composite is done by using stir casting followed by centrifugal casting method. Initially aluminium LM13 alloy is taken in a graphite crucible and then melted (760 ^{0}C) in an electric furnace. Inert gas atmosphere is maintained to avoid chemical reaction. When the metal is fully melted, pre heated B_4C particles (300 ^{0}C) are added into the molten metal and stirred at 300 rpm for 5 min to obtain uniform distribution. This is then followed by centrifugal casting to get FGM properties. The molten metal obtained from stir casting is poured into a pre heated (350 ^{0}C) rotating die for centrifugal casting. Figure 1 shows the sequence of steps in the fabrication process. The casting is done at a die speed of 1000 rpm. Cylindrical specimens are obtained with dimensions 150 x 150 x 15 mm.

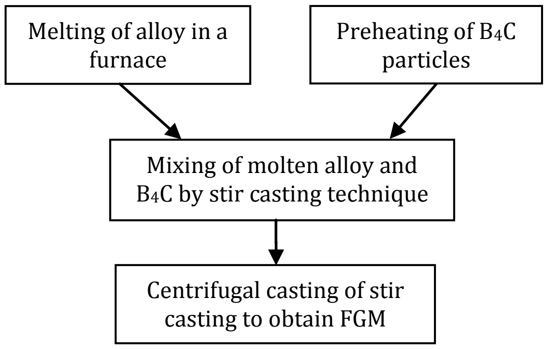

Fig. 1. Fabrication process flow chart.

2.2 Heat Treatment Process

The composite specimens are machined from the castings and undergo heat treatment process. The heat treatment process involves 3 stages namely solution treatment, aging and cooling. The solution treatment is done at 525 °C for 5 hrs. These samples are then aged separately at the temp 150 °C, 175 °C and 200 °C for an aging time of 2 hrs, 6 hrs and 10 hrs and then allowed to cool naturally.

2.3 Optimization Methodology

Influence of parameters like applied load, aging temperature and aging time on the heat treated Al LM13/ B4C composite is done using Taguchi method. Effect of above mentioned parameters is studied by considering their interaction using ANOVA (Analysis Of Variance) technique. Experiments are done by including the three parameters applied load, aging temperature and aging time for three levels (Table 2).

Table 2. Levels of parameters.

Level	Applied Load (N)	Aging Temperature (°C)	Aging Time (hrs.)
1	10	150	2
2	20	175	6
3	30	200	10

2.4 Adhesive wear test

The wear test is carried on the outer periphery of functionally graded composite samples as per L_{27} orthogonal array by using a pin-on-disc tribometer. The pin on disc consists of a horizontal rotating disc and a dead load pin. A group of weights connecting the fulcrum through a beam provides the normal force on the pin. The rotation rate and radius of the pin are controlled so that constant contact is provided at various sliding parameters. The composite specimen is prepared with size (10x10 mm) by performing milling along the radial direction.

The wear test is done at a constant velocity of 2.4 m/sec and a constant sliding distance of 1300 m. The outer surface of heat treated FGM specimens is subjected to wear test by holding against a rapidly rotating disc. Wear rate is calculated using mass loss formula for which weight of specimen before and after performing the wear test is measured.

3. RESULTS AND DISCUSSION

The experiment is aimed to find the influence of various important factors on the wear process to achieve minimum wear rate. The experiments are developed based on the orthogonal array in order to relate the influence of applied load, aging temperature and aging time. Major influencing parameter on the wear rate is found by analyzing S/N ratios.

3.1 Tribological behavior

The wear rate of the heat treated composite is calculated for all 27 experiments obtained from orthogonal array. The wear rate is shown in Table 3.

3.2 Signal-to-Noise ratio Analysis

Signal to Noise (S/N) ratio in Taguchi method shows the ranking of parameter considering their influence. Table 4 shows the response table for the S/N ratio and “smaller-the-better” criteria is considered for analysis. The difference of the peak values gives the corresponding delta value. Ranking is given in the decreasing order of the obtained value. Considering the wear rate, load has major influence which is followed by the influence of aging temperature and aging time (Table 4).

Table 3. Experimental conditions and obtained wear rate.

S. No.	Temperature (°C)	Aging time (hrs.)	Load (N)	Wear rate (mm^3/m)
1	150	2	10	0.00190
2	150	2	20	0.00283
3	150	2	30	0.00398
4	150	6	10	0.00177
5	150	6	20	0.00266
6	150	6	30	0.00377
7	150	10	10	0.00183
8	150	10	20	0.00275
9	150	10	30	0.00393
10	175	2	10	0.00152
11	175	2	20	0.00244
12	175	2	30	0.00362
13	175	6	10	0.00129
14	175	6	20	0.00216
15	175	6	30	0.00325
16	175	10	10	0.00130
17	175	10	20	0.00219
18	175	10	30	0.00338
19	200	2	10	0.00163
20	200	2	20	0.00254
21	200	2	30	0.00373
22	200	6	10	0.00138
23	200	6	20	0.00227
24	200	6	30	0.00335
25	200	10	10	0.00140
26	200	10	20	0.00230
27	200	10	30	0.00346

Table 4. Response table for S/N ratio.

Level	Temperature (°C)	Aging time (hrs.)	Load (N)
1	51	51.73	56.15
2	53.12	52.83	52.16
3	52.70	52.61	48.85
Delta	1.77	1.10	7.30
Rank	2	3	1

4. INFLUENCE OF PARAMETERS ON RESPONSE

The effect on various parameters influencing the wear rate is plotted as shown in the following Figs. 2 and 3. Mean plot in the Fig. 2 explains the trend of corresponding responses. From Fig. 3 the optimum parameters for enhancing the tribological behavior are inferred as a low load of 10 N and an aging temperature of 175 ^{0}C for an aging period of 6 hrs. Influence of parameters on the response to wear is discussed accordingly.

4.1 Effect of temperature

From Fig. 2 it is observed that initially wear rate decreases with increase in temperature (175 °C) and then with further increment of temperature (200 °C) the wear rate increases but the value is lesser than that of initial wear rate corresponding to temperature (150 °C). When aging is done at temperature 150 °C, the phases of the B_4C in aluminium MMC are granular and the particle forms cluster and lower wear resistance is observed. With the increase in the aging temperature (175 °C), the size as well as the morphology of the coarse particles probably be refined slightly due to the thermal diffusion at phase interface and also the B_4C particles phase in matrix transforms to uniform phase. This uniformity of B_4C phase helps the functionally graded composite in carrying load and exhibit better wear properties. With the further increase in temperature (200 °C), the particles get precipitated at the grain boundaries which will reduce the wear resistance of the composite.

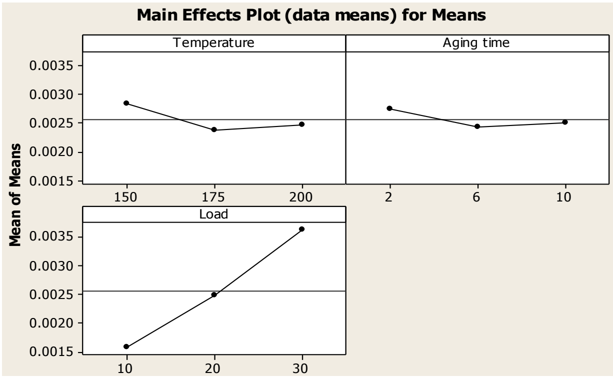

Fig. 2. Main Effect Plot (data means) for means.

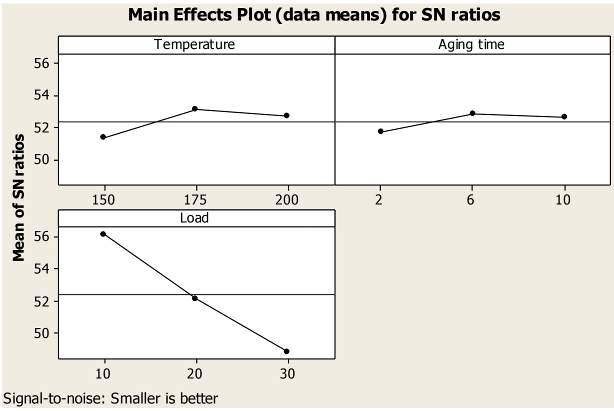

Fig. 3. Main Effect plot (data means) for SN ratio.

4.2 Effect of aging time

From Fig. 2 it is inferred that wear rate decreases drastically from aging time 2 hrs to 6hrs and for aging time 10 hrs, slightly increasing trend is observed. This trend in the wear behavior could probably due to over aging at 10 hrs. The microstructure of the grain is more refined and able to carry higher loads at when the functionally graded composite is aged for time duration of 6 hrs.

4.3. Effect of load

The influence of applied load on the wear behavior is explained from the Fig. 2. It is observed that wear rate increases with increase in the load almost in a linear pattern for loads (10 N, 20 N, 30 N). As the load increases the pressure applied will increase and therefore plastic deformation happens and this result in increase of wear rate. Therefore the MMC shows higher wear rate at high load.

5. ANALYSIS OF VARIANCE

ANOVA results for the wear rate are shown in the Table 5 which reveals the major influence parameters on the performance characteristics. The following analysis was carried out for a level of significance of 5 %. Major influence of the parameter is indicated by a p value less than 0.05. From the ANOVA table it is concluded that the aging time (92.12 %) has a major influence on the wear rate followed by influence of aging temperature (5.36 %) and applied load (1.95 %).

6. SCANNING ELECTRON MICROSCOPE ANALYSIS

Scanning Electron Microscopy (SEM) is performed on worn out specimens to understand the wear mechanism on the composite surface. Figure 4 (a-c) shows the SEM pictures of FGM specimens for different aging time (2 hrs, 6 hrs, 10 hrs) at constant load (10 N) and constant aging temperature (175 °C).SEM shows that the material removal rate with severe delamination is observed when the aging time is 2 hrs (Fig. 4a) and the material removal ratewith few scratches is seen when the aging time is 6 hrs (Fig. 4b). The depth and number of grooves increased when it is further aged for 10 hrs (Fig. 4c) compared with that observed when the aging is done for 6hrs. SEM of the functionally graded specimens for various loads at constant aging time (6 hrs) and aging temperature (175 °C) is also analyzed to know the effect of load on the wear behavior. The surface (Fig. 4b) shows shallow grooves with less material removal at a load of 10 N. With increase in loads (20 N, 30 N) the scratches as well as the depth of penetration increases which indicates higher wear rate (Fig. 5a and Fig. 5b). Mild wear to severe wear occurs as the load increases. Hence severe delamination is observed at high load (30 N).But, the time taken for transition is observed to be more due to segregation of reinforcements at the outer periphery of FGM.

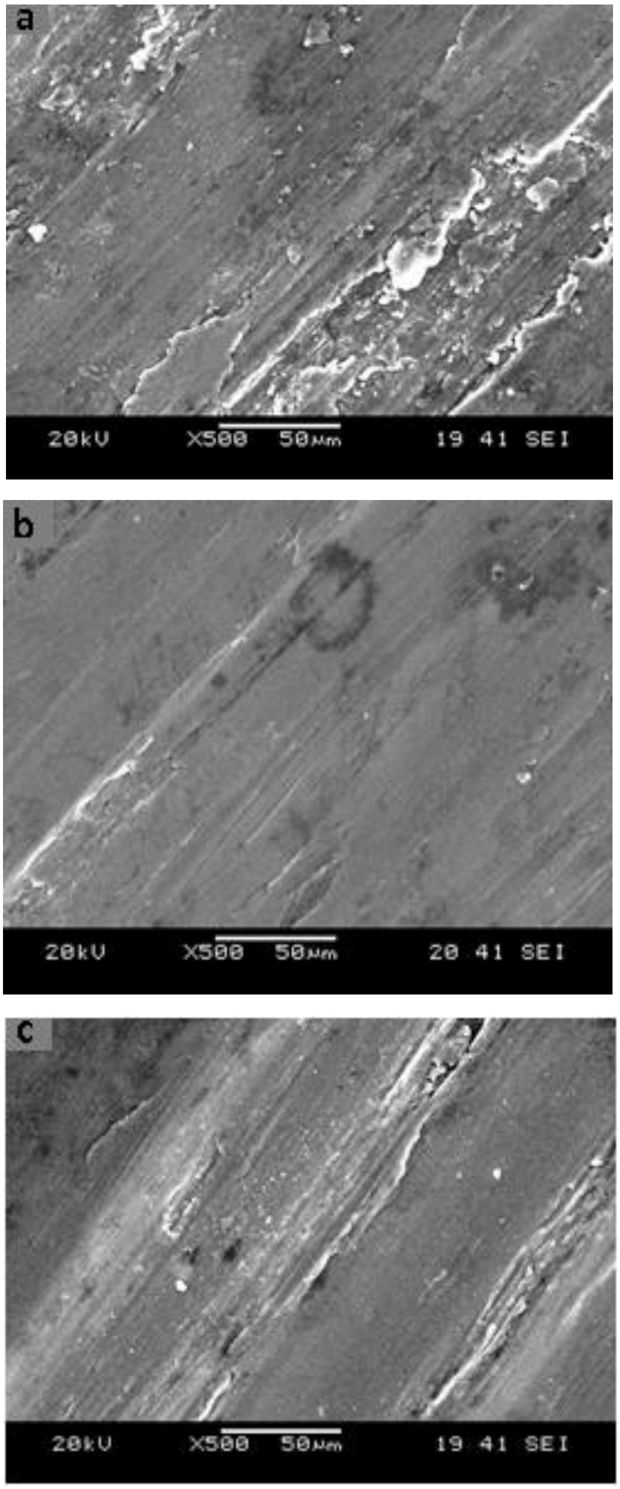

Fig. 4. SEM analysis of worn out specimens for different aging times (a) 2 hrs; (b) 6 hrs; (c) 10 hrs.

Table 5. Analysis of Variance results.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage (%)
Temperature	2	0.0000011	0.0000011	0.0000005	1289.44	0.000	5.36
Load	2	0.0000004	0.0000004	0.0000002	516.26	0.000	1.95
Aging time	2	0.0000189	0.0000189	0.0000094	22.75	0.000	92.19
Temperature*aging time	4	0.0000000	0.0000000	0.0000000	23.42	0.878	0.00
Temperature * load	4	0.0000000	0.0000000	0.0000000	0.29	0.011	0.00
Load*Aging time	4	0.0000000	0.0000000	0.0000000	6.68		0.00
Error	8	0.0000000	0.0000000	0.0000000			0.00
Total	26	0.0000205	0.0000205				

Note: DF=Degree of Freedom, Seq SS=Sequential Sum of square, Adj SS=Adjacent Sum of Square, Adj MS=Adjacent mean Square, F=Fisher's test.

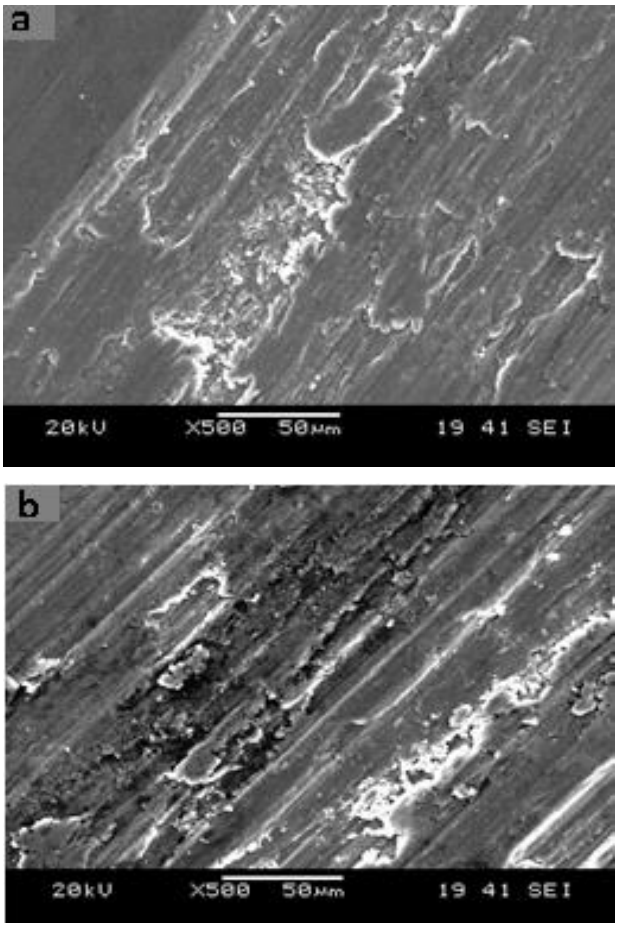

Fig. 5. SEM analysis of worn out specimens at varying load (a) 20 N; (b) 30 N.

7. CONCLUSION

Al LM13 alloy along with a 10 wt.% of boron carbide particles is successfully fabricated using stir casting followed by centrifugal casting technique to obtain FGM properties. It is then subjected to heat treatment process for further improvement of properties. It is inferred from tribological behavior that wear rate has a direct relation with load and fluctuating variation with aging temperature and time. Aging time has a major influence (92.19 %) in detecting the wear extent followed by aging temperature (5.36 %) and applied load (1.95 %). Optimal condition for good tribological behavior is obtained as low load 10 N along with aging temperature 175 °C and for a aging time of 6 hrs. SEM analysis revealed that higher wear rate is observed at high load as well as the specimen aged at 10 hrs. FGM delays the transition period from mild wear to severe wear as the outer periphery of the composite is particle rich zone due to centrifugal casting. The present research on the tribological behavior of aluminium MMC can be used in sorting out the best materials for various applications where surface requires better wear properties. Many of the automobile parts like piston rings, cylinder block, brake drum etc., can be manufactured using this FGM which is heat treated at optimum conditions.

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