

Sliding Wear Response of Beryl Reinforced Aluminum Composite - A Factorial Design Approach

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Abstract. Al-Beryl MMCs were successfully fabricated using powder metallurgy route. Processing conditions such as beryl content and particle size were varied and its influence on dry sliding wear response was studied. Effect of test parameters like applied load and sliding distance on wear performance of Al-Beryl MMCs were discussed detail. Sliding wear tests were conducted using a pin on disc machine based on the 2⁴ (4 factors at 2 levels) factorial design. Analysis of variance (ANOVA) was performed to obtain the contribution of control parameters on wear rate. The present study shows that wear resistance of Al-beryl MMCs not only depends on the beryl content but also influenced by normal load, sliding distance and particle size. The results show that most significant variables affecting wear rate of Al – beryl MMCs are size of the beryl particles (22%), beryl content (19.60%), sliding distance (18.47%), and normal load (10.30%). The interaction effects of these parameters are less significant in influencing wear rate compared to the individual parameters. The correlation between sliding wear and its parameters was obtained by multiple regression analysis. Regression model developed in the present study can be successfully implemented to predict the wear response of Al-Beryl MMCs.

1. Introduction

Aluminium metal matrix composites (AMMCs) possess unique properties such as high elastic modulus, tensile strength and wear resistance [1] and are used as brake rotors, pistons, connecting rods, engine blocks and bearings [2]. Worldwide attention has been focused on the processing and fabrication of AMMCs due to favorable manufacturing costs and performance [3]. Two major processing techniques that have been found suitable for these composites are powder metallurgy (P/M) and liquid metallurgy vortex technique (LMVT) [4]. The most commonly employed metal matrix composite system consists of Al reinforced with hard ceramic particles usually silicon carbide and alumina [5, 6]. These composite materials showed different strengthening mechanisms when compared with conventional metallic materials [7]. The presence of hard ceramic particles has endowed these composites with improved tribological characteristics. These properties along with good specific

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strength and modulus make them good candidate materials for many engineering applications where sliding contact is experienced. Among various ceramic additions to Al, SiC has been given greater attention by many researchers. However, Al-SiC MMCs still has some limitations such as the formation of Al_4C_3 during high temperature synthesis, which impairs poor mechanical properties. Thus, efforts have been made to overcome such problems by incorporating reinforcing materials such as beryl which is naturally occurring ceramic material. AMMCs generally possess superior wear resistance compared with unreinforced aluminum. The processing conditions that control the wear performance of Al-Beryl MMCs are beryl content and size of the beryl particles. Quantitative analysis of reinforcement distribution in Al matrix is not widely studied. Moreover, a homogeneous distribution of reinforcement is responsible for increased wear resistance [11–13]. The present work is focused to study the influence of processing conditions such as beryl content and beryl particle size on dry sliding wear behaviour of Al-Beryl MMCs. Also, the work is aimed to understand the effect of variation of test parameters like applied load and sliding distance on wear performance of Al-Beryl MMCs.

2. Materials and Processing

Al powder having a density of 2.71 g/cc and beryl with density 2.64 g/cc were taken as starting materials. The chemical composition of Al and beryl is shown in Table 1 and 2. Beryl with chemical formula $Be_3Al_2Si_6O_{18}$ is a naturally occurring ceramic particle which is abundantly found in many parts of India. Processing of AMMCs using LMVT showed a non uniform distribution of ceramic particles in Al matrix due to the difference between the densities of Al matrix and reinforcement material. As a result, beryl having a density almost nearer to density of Al was selected as a reinforcement particle.

Table1. Chemical composition of Al

Element	Si	Fe	Al
Wt. %	0.14	0.16	Balance

Table2. Chemical composition of beryl [14]

Element	SiO ₂	Al ₂ O ₃	BeO	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO
Wt. %	65.4	17.9	12.3	0.8	1.34	0.48	0.55	0.004	0.05

Many processing methods such as LMVT and P/M are available for fabrication of AMMCs. In case of LMVT matrix is melted in a crucible and reinforcement particles are added to the molten Al. The process can produce efficient castings of AMMCs but has a limitation. The weight percentage of reinforcement cannot be more than 15 Wt. %. Increasing particle size leads to more pull-off force due to Vander walls forces in which attraction depends on first power of particle size. It means increasing particle size leads to increasing Vander walls forces which may lead to non uniform distribution of reinforcement in casting. On the other hand, researchers have showed many limitations for using nano and sub-micron sized reinforcement particles in LMVT because of their tendency to agglomerate. Large difference in densities between the matrix and reinforcement may also lead to settling down of reinforcement particles while processing through LMVT. To overcome such problems P/M is used to fabricate Al – Beryl MMCs. In case of P/M, reinforcement up to 30 Wt. % can be added to the Al matrix without any settling down problems. As a result, the distribution of beryl in Al matrix is expected to be uniform. Beryl was procured in the form of stones and was crushed to powder form using a ball mill. A proper ball to powder ratio was maintained to avoid powder agglomeration. Crushed beryl particles were sieved to segregate into various sizes. Particle Size Analysis (PSA) was

carried out after sieving. Fabrication of Al-Beryl MMCs was carried out by varying the size of the beryl particles and beryl content. Beryl particles of sizes 108 μm (coarse) and 38 μm (fine) were used to fabricate Al-Beryl MMCs. Percentage of beryl content was varied by 5%, 10% and 15% by weight.

3.0 Experiment

3.1 Sliding wear test

Dry sliding wear test was conducted on Al-Beryl MMCs using a pin-on-disc test apparatus as per ASTM G99-95 standards. The standard wear specimen (pin) having a diameter of 10mm and 40 mm height was required to perform wear test. Sintered Al-Beryl samples were having a thickness of 10 mm. These samples were adhered to a steel pin to obtain required thickness as shown in Figure 1.

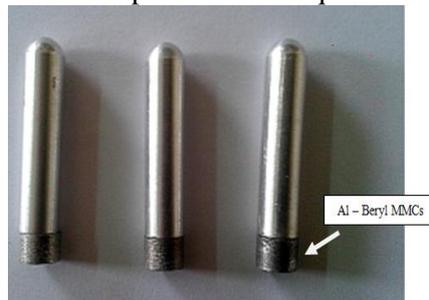


Figure 1. Wear test specimens of Al – Beryl MMCs

Before wear testing, the specimen surface was polished with a 400-grit emery paper to permit proper contact between the specimen surface and the abrasive media. The initial weight of the specimen was measured in a single pan electronic weighing machine with least count of 0.0001 g. During the test the pin was pressed against EN32 steel disc by applying the normal load of 0.5 and 0.75 kg. After running through a fixed sliding distance, the specimens were removed, cleaned with acetone, dried and weighed to determine the weight loss due to wear. The difference in the weight measured before and after test gave the sliding wear of the composite specimen and then the volume loss was calculated. The sliding wear of the composite was studied as a function of the volume percentage of the reinforcement, sliding distance, the applied load and the sliding distance.

3.2 2^k Factorial Design

Estimating the effects of factors like percentage reinforcement of beryl, Size of beryl particles, load and sliding distance on wear rate with a minimal number of tests is crucial for being able to optimize the output of the process [15]. Factorial Experiments are used to investigate the effects of two or more factors on the output response of a process. The major advantage of this technique is to find out the possible interaction between the parameters. A two-level full factorial design of experiments was used in the present study. Four parameters were varied on two levels i.e. upper level and lower level. The upper level and lower level of the four parameters i.e. beryl percentage, applied load, sliding distance and size of beryl particles used in the present study are reported in Table 3. To develop the linear regression equation from the experimental values, one must conduct at least 2^k number (where k stands for number of parameters) of experiments. Following this concept, sixteen sets of wear test experiments as reported in Table 4 were conducted and each set was repeated three times. The average of the response variables were used for the calculation. The upper level of beryl percentage, applied load, sliding distance and beryl particle size are 15 wt%, 0.75 kg, 1200 m and 108 μm respectively. The lower level of beryl percentage, applied load, sliding distance and beryl particles size are 5 wt%, 0.5 kg, 400 m and 38 μm respectively.

Table 3. Process parameters with their values at two levels

	A	B	C	D
Design factor level	Beryl percentage (%) by Wt	Load (kg)	Sliding Distance (m)	Beryl particle size (μm)
Low (-)	5	0.5	400	38
High (+)	15	0.75	1200	108

Table 4. Variation of parameters based on 2^4 design

Test Run	Beryl (%) by Wt (A)	Load (kg) (B)	Sliding Distance (m) (C)	Beryl particle size (μm) (D)
1	-1	-1	-1	-1
2	+1	-1	-1	-1
3	-1	+1	-1	-1
4	+1	+1	-1	-1
5	-1	-1	+1	-1
6	+1	-1	+1	-1
7	-1	+1	+1	-1
8	+1	+1	+1	-1
9	-1	-1	-1	+1
10	+1	-1	-1	+1
11	-1	+1	-1	+1
12	+1	+1	-1	+1
13	-1	-1	+1	+1
14	+1	-1	+1	+1
15	-1	+1	+1	+1
16	+1	+1	+1	+1

In order to find the significance of each parameter a design matrix as shown in Table 5 has been developed. The effect beryl reinforcement percent by weight on wear rate of Al – Beryl MMC is calculated using equation (1).

$$\text{Effect of reinforcement \% (A)} = \frac{[(a) - (b) + (c) - (d) + (ab) - (ac) + (ad) - (bc) + (bd) - (abc) + (abd) - (acb) + (bcd) - (abcd) - (1)]}{2n} \quad (1)$$

Similar equations were used to find the effect of other parameters and their interactions. In 2^k designs, the magnitude of the factor effects indicates which variables are important. Analysis of variance (ANOVA) was used to confirm the significant factors.

3.3 Multiple Regressions

The relationship between the control parameters (Reinforcement percent (A), normal load (B), Sliding Distance (C), Particle Size (D)) and the output performance (wear rate) are obtained by multiple regression analysis. Ultimately, the following regression models are fitted to the wear rate.

Table 5. Matrix design for finding significance of each parameter and their interactions

Sno	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	ABCD
1	-1	-1	-1	-1	1	1	-1	1	1	1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1
3	-1	1	-1	-1	-1	1	-1	-1	-1	1	1	1	-1	1	-1
4	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1
5	-1	-1	1	-1	1	-1	-1	-1	1	-1	1	-1	1	1	-1
6	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1
7	-1	1	1	-1	-1	-1	-1	1	-1	-1	-1	1	1	-1	1
8	1	1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	-1	-1
9	-1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	1	-1
10	1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1
11	-1	1	-1	1	-1	1	1	-1	1	-1	1	-1	1	-1	1
12	1	1	-1	1	1	-1	1	-1	1	-1	-1	1	-1	-1	-1
13	-1	-1	1	1	1	-1	1	-1	-1	1	1	1	-1	-1	1
14	1	-1	1	1	-1	1	1	-1	-1	1	-1	-1	1	-1	-1
15	-1	1	1	1	-1	-1	1	1	1	1	-1	-1	-1	1	-1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

$$W = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 AB + \beta_6 AC + \beta_7 AD + \beta_8 BC + \beta_9 BD + \beta_{10} CD + \beta_{11} ABC + \beta_{12} ABD + \beta_{13} ACD + \beta_{14} BCD + \beta_{15} ABCD \quad (2)$$

where W is the wear rate, $\beta_0, \beta_1, \beta_2, \dots, \beta_{15}$ are the constants, A, B, C and D are the coded values of the parameters. β_0 is the coefficient indicating the response variables at the lower level (i.e. at A = -1 (5% beryl), B = -1 (0.5 kg), C = -1 (400 m) and D = -1 (38 μm)). The value of constant (β_0) in the previous equation is the intercept of the plane and is a mean response value for the entire experiments conducted [16].

4.0 Results and Discussion

4.1 Particle size analysis (PSA)

Particle size influences many properties of particulate materials and is a valuable indicator of quality and performance. The size and shape of powders influences flow and compaction properties. Particle size analysis of beryl powders is carried out using Mastersizer 2000, which confirms to ISO13320-1 guidelines. The results are shown in Figure 2 and Figure 3. It can be observed from PSA results that the samples collected after sieving were in the range of 108 μm and 38 μm .

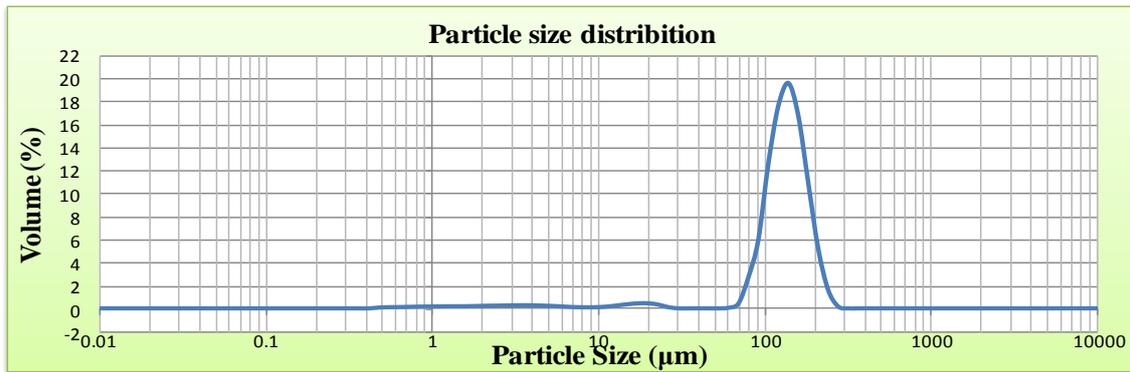


Figure 2. Beryl with average particle size of 108 μm

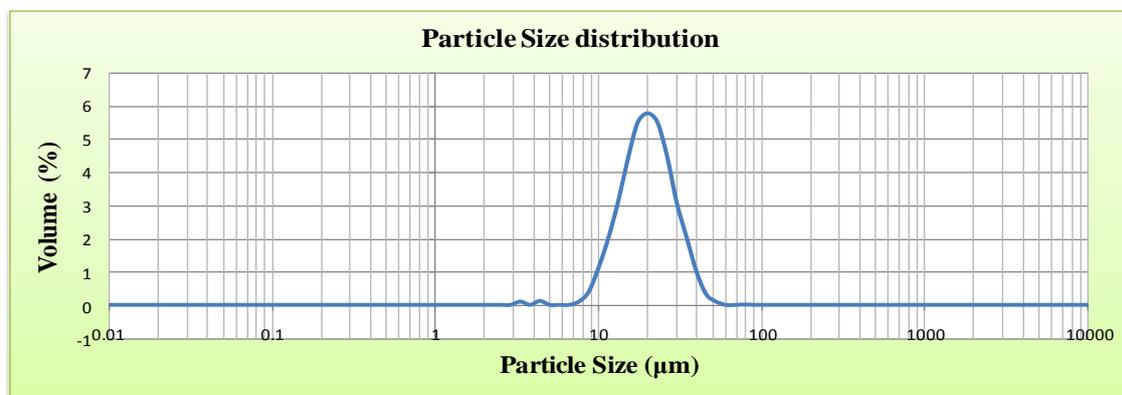


Figure 3. Beryl with average particle size of 38 μm

4.2 Optical studies

Scanning electron microscope (SEM) images of Al powder as in Figure 4 shows aluminum particles were of uniform size and there are no flakes present in the powder. SEM images of crushed beryl powders were shown in Figure 5 which confirms that there is no particle agglomeration and also the shape of the particles was uniform.



Figure 4. SEM image of Al Powder

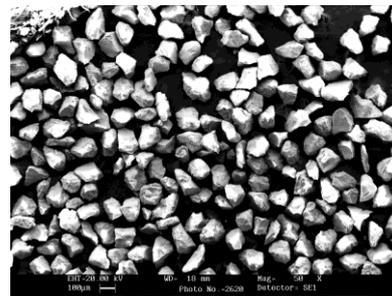


Figure 5. SEM image of beryl Powder

Optical images of Al – beryl MMCs were shown in Figure 6. It can be observed that beryl particles were uniformly distributed throughout the matrix.

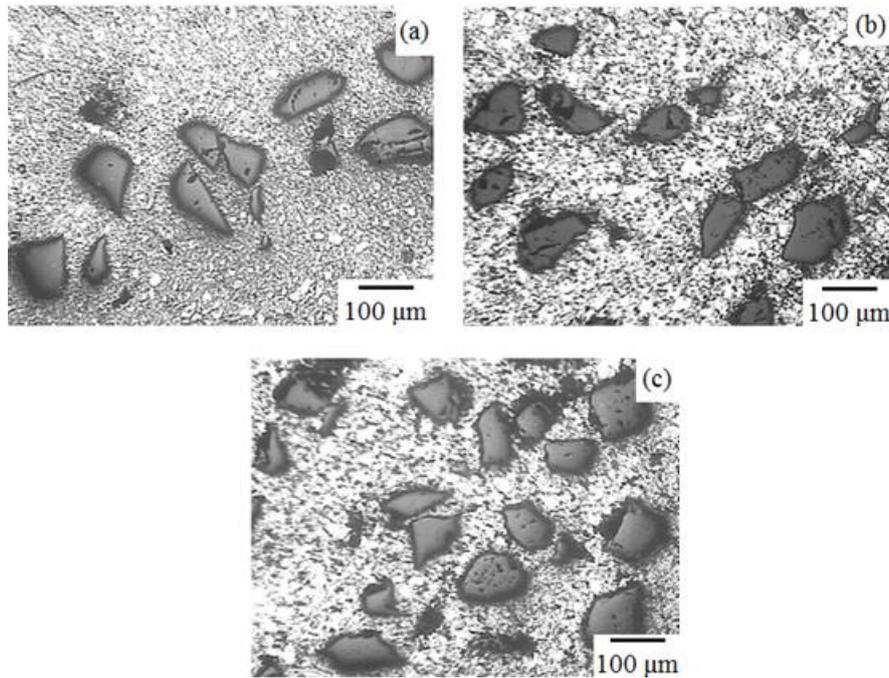


Figure 6. Optical images of Al – Beryl MMCs at X 500
(a) 5% Beryl, (b) 10% Beryl, (c) 15% Beryl

4.3 Effect of Control Parameters on Wear Rate

The design matrix for four parameters each at two levels along with the results of the wear tests are presented in Table 6. Effect of beryl reinforcement on wear rate was found using equation (1). Similar equations were used to find the effect of other parameters and their interactions. The effects of these parameters and their contribution on wear rate are listed in Table 7.

Table 6. 2^4 design for sliding wear test

Test Run	Beryl (%) by Wt (A)	Load (kg) (B)	Sliding Distance (m) (C)	Beryl particle size (μm) (D)	Wear rate ($\mu\text{g/m}$) (Response)
1	-1	-1	-1	-1	4.25
2	+1	-1	-1	-1	3.50
3	-1	+1	-1	-1	4.50
4	+1	+1	-1	-1	3.75
5	-1	-1	+1	-1	3.00
6	+1	-1	+1	-1	1.83
7	-1	+1	+1	-1	3.92
8	+1	+1	+1	-1	2.17
9	-1	-1	-1	+1	6.50
10	+1	-1	-1	+1	4.25
11	-1	+1	-1	+1	8.50
12	+1	+1	-1	+1	5.30
13	-1	-1	+1	+1	4.68
14	+1	-1	+1	+1	2.85
15	-1	+1	+1	+1	5.58
16	+1	+1	+1	+1	4.08

Table 7. Effect and Contribution of parameters and their effects

Factor	Effect	% Contribution	Factor	Effect	% Contribution
A	-1.65	19.6	BD	0.4275	5.078
B	0.8675	10.3	CD	-0.285	3.385
C	-1.555	18.47	ABC	0.0875	1.039
D	1.8525	22	ABD	-0.005	0.059
AB	-0.15	1.782	ACD	0.4425	5.256
AC	0.0875	1.039	BCD	-0.21	2.494
AD	-0.545	6.474	ABCD	0.2325	2.762
BC	-0.02	0.237			
A : Beryl Reinforcement (% wt)			C : Sliding Distance (m)		
B : Load (kg)			D : Beryl Particles Size (μm)		

It can be observed from Table 7 that the effect of beryl content was negative indicating that increasing the beryl content from low level (5% by weight) to a high level (15% by weight) will decrease the wear rate. This is attributed to the increase of hardness with beryl concentration. The depth of wear grooves depends on the hardness of the specimen surface. The higher the hardness, the more shallow and finer is the wear grooves, thus leading to less wear rate. Effect of load during wear test is positive indicating that increasing the load from low level (0.5 kg) to high level (0.75 kg) will increase the wear rate. Effect of size of beryl particles on wear rate is positive which indicates that on increasing the particle size of the beryl from low level (38 μm) to a high level (108 μm) will increase wear rate. It is reported that the wear rate depends on the actual microscale contact made by the beryl particles [17, 18]. With the increase of beryl particle size, the effective load on each particle increases due to variation in actual contact area and they have greater tendency for large penetration. This leads to deeper and wider abrasive grooves and finally causes more wear. The percentage contribution of each parameter and their interactions are documented in Table 7. It can be observed that the beryl content (19.6%), the normal load (10.3%), the sliding distance (18.47%) and the size of beryl particles (22%) are significant factors that affect the wear performance of Al-Beryl MMCs than their interactions. The interaction between beryl content and beryl particle size (6.47%) is the significant interaction model terms.

4.4 Statistical Analysis of Variance (ANOVA)

ANOVA is a statistical design method used to break up the individual effects from all control factors. The percentage contribution of each control factor is employed to measure the corresponding effect on the quality characteristic [19]. Tables 7 show the results of statistical analysis of variance. The error contribution in the ANOVA for wear rate is very less. The present analysis indicates that control parameters selected in the study have both statistical and physical significance as the percentage contribution is greater than the error.

Table 8. Analysis of Variance

Source	SS	Df	MS	F Test	p-value
Model	2.14	4	0.53	53.86	0.0001
Beryl Reinforcement (A)	0.63	1	0.63	63.27	0.0001
Load (B)	0.16	1	0.16	15.89	0.0021
Sliding Distance (C)	0.6	1	0.6	60.26	0.0001
Particle Size (D)	0.75	1	0.75	76.02	0.0001
Error	0.11	11	0.009917		
Total	2.25	15			

SS – Sum of Squares, df – Degrees of Freedom, MS – Mean Square

4.5 Regression analysis

The constants $\beta_0, \beta_1, \beta_2, \dots, \beta_{15}$ are evaluated and equation (2) has been modified accordingly to predict the wear rate.

$$W = 4.291 - 0.825 A + 0.43375 B - 0.7775 C + 0.92625 D - 0.075 AB + 0.0438 AC + 0.9263 AD - 0.01 BC + 0.2138 BD - 0.1425 CD + 0.0438 ABC - 0.0025 ABD + 0.2213 ACD - 0.1050 BCD + 0.1163 ABCD \quad (3)$$

2^k factorial design and ANOVA tests confirm that main effect of the parameters are significant than their interactions and hence the equation (3) was modified by neglecting the interactions of the parameters.

$$W = 4.291 - 0.825 A + 0.43375 B - 0.7775 C + 0.92625 D \quad (4)$$

The validity of equation (4) was tested by conducting a series of tests at randomly selected levels of experimental parameters. The calculated values under such selected experimental parameters were compared with the experimental values. During the calculation of the wear rate under selected experimental conditions, the coded values of the experimental parameters were considered. The experimental values along with the calculated values of the wear rate based on equation (4) are reported in Table 9. The variations between the experimental and the calculated values as reported in Table 9 are very less.

Table 9. Comparison of experimental values with the calculated values

Sno	Beryl Reinforcement (Wt. %)	Normal Load (kg)	Sliding Distance (m)	Beryl particle size (μm)	Wear rate ($\mu\text{g} / \text{m}$)	
					Experimental	Theoretical
1	5 (-1)	0.5 (-1)	400(-1)	38 (-1)	4.250	4.5335
2	5 (-1)	0.5 (-1)	400(-1)	108 (+1)	6.500	6.3860
3	5 (-1)	0.5 (-1)	800(0)	38 (-1)	3.630	3.7560
4	5 (-1)	0.5 (-1)	800(0)	108 (+1)	5.130	5.6085
5	5 (-1)	0.5 (-1)	1200(1)	38 (-1)	3.000	2.9785
6	5 (-1)	0.5 (-1)	1200(1)	108 (+1)	4.680	4.8310
7	10 (0)	0.5 (-1)	400(-1)	38 (-1)	3.750	3.7085
8	10 (0)	0.5 (-1)	400(-1)	108 (+1)	5.250	5.5610
9	10 (0)	0.5 (-1)	800(0)	38 (-1)	2.750	2.9310
10	10 (0)	0.5 (-1)	800(0)	108 (+1)	4.500	4.7835
11	10 (0)	0.5 (-1)	1200(1)	38 (-1)	2.250	2.1535
12	10 (0)	0.5 (-1)	1200(1)	108 (+1)	4.030	4.0060
13	15 (+1)	0.5 (-1)	400(-1)	38 (-1)	3.500	2.8835
14	15(+1)	0.5 (-1)	400(-1)	108 (+1)	4.250	4.7360
15	15(+1)	0.5 (-1)	800(0)	38 (-1)	2.500	2.1060
16	15(+1)	0.5 (-1)	800(0)	108 (+1)	3.000	3.9585
17	15(+1)	0.5 (-1)	1200(1)	38 (-1)	1.830	1.3285
18	15(+1)	0.5 (-1)	1200(1)	108 (+1)	2.850	3.1810
19	5 (-1)	0.75 (+1)	400(-1)	38 (-1)	4.500	5.4010
20	5 (-1)	0.75 (+1)	400(-1)	108 (+1)	8.500	7.2535
21	5 (-1)	0.75 (+1)	800(0)	38 (-1)	4.250	4.6235
22	5 (-1)	0.75 (+1)	800(0)	108 (+1)	7.000	6.4760
23	5 (-1)	0.75 (+1)	1200(1)	38 (-1)	3.920	3.8460
24	5 (-1)	0.75 (+1)	1200(1)	108 (+1)	5.580	5.6985

25	10 (0)	0.75 (+1)	400(-1)	38 (-1)	4.000	4.5760
26	10 (0)	0.75 (+1)	400(-1)	108 (+1)	7.050	6.4285
27	10 (0)	0.75 (+1)	800(0)	38 (-1)	3.370	3.7985
28	10 (0)	0.75 (+1)	800(0)	108 (+1)	5.450	5.6510
29	10 (0)	0.75 (+1)	1200(1)	38 (-1)	3.000	3.0210
30	10 (0)	0.75 (+1)	1200(1)	108 (+1)	4.690	4.8735
31	15 (+1)	0.75 (+1)	400(-1)	38 (-1)	3.750	3.7510
32	15 (+1)	0.75 (+1)	400(-1)	108 (+1)	5.300	5.6035
33	15 (+1)	0.75 (+1)	800(0)	38 (-1)	2.750	2.9735
34	15 (+1)	0.75 (+1)	800(0)	108 (+1)	4.750	4.8260
35	15 (+1)	0.75 (+1)	1200(1)	38 (-1)	2.170	2.1960
36	15 (+1)	0.75 (+1)	1200(1)	108 (+1)	4.080	4.0485

5.0 Conclusions

Al-Beryl MMCs were successfully prepared by P/M and synthesized to dry sliding wear test. Effect of processing conditions such as beryl content and particle size were varied and its influence on dry sliding wear response was studied. Test parameters like applied load and sliding distance were varied and studied in detail. 2^k factorial design approach was successfully implemented to find out the significance of individual parameters and their interactions. ANOVA was used to confirm the results of 2^k factorial design approach. A linear regression equation was developed to predict the wear rate at the intermediate points and the equation was validated using experimental values. A complete analysis of worn out surfaces were carried out using scanning electron microscope. The following conclusions were drawn from the present study

- (i) Factorial design approach is an excellent tool and is used to identify the significance of various parameters on wear rate.
- (ii) Effect of processing conditions like beryl content, particle size and effect of test parameters like normal load and sliding distance are more significant than their interactions on wear behavior of Al-Beryl MMCs.
- (iii) Interaction between beryl content and particle size has greater influence on wear behavior of Al-Beryl MMCs among all other interactions.
- (iv) The percentage contribution of beryl content, normal load, sliding distance and beryl particle size are 19.6%, 10.3%, 18.47% and 22% respectively.
- (v) The influence of beryl particle size has more effect on wear behavior of Al-Beryl MMCs
- (vi) Regression equation developed during the present study can be successfully implemented to predict the wear behavior of Al-Beryl MMCs.

6. References

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