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The Effect of Cryogenic Treatment on the Wear Resistance of Al Alloy-Fly Ash Composites

D.PrasannaVenkatesh, P.Shanmughasundaram

Abstract: *The effect of cryogenic treatment on the wear resistance of aluminium alloy LM 25, LM25+5 % fly ash and LM25+10% fly ash composites, which are synthesized by squeeze casting method, was investigated. The impact of the parameters on the wear resistance was studied under two different cryogenic soaking periods [0hrs (untreated), 12hrs and 24 hrs.] and three different load and sliding velocities with the help of pin-on-disc test rig. The wear tests were performed according to Taguchi's approach. The percentage contribution of the cryogenic soaking period was determined by means of analysis of variance. The load was found to be more significant than cryogenic soaking period and velocity on wear loss of the composites. Regression model was generated to envisage the wear loss.*

***Keywords** - Al alloy - fly ash MMC, squeeze casting, wear resistance, cryogenic soaking period, Taguchi, ANOVA*

I.INTRODUCTION

Metal Matrix Composites (MMCs) are generally used for wear applications owing to their superior properties compared to alloys [1]. MMCs are employed in a wide range of areas like aerospace and automobile applications [2]. The wear rate of aluminiumSiC MMC was investigated with the help of a pin-on-disc type wear rig. It was reported that wear rate increased with increasing load and sliding distance [3]. Wear resistance of Al alloy Al6061-based nano composites was investigated. The hardness of the nano composite was 73% more than that of base alloy. It was reported that the MMCs displayed an enhanced wear resistance compared to the base material [4]. AA2218–Al_2O_3 (TiO_2) composites are fabricated by stirring method. Sliding wear increases linearly with distance while it decreases with weight percentage of particle at a given load. Minimum wear is recorded in 5 wt% composite caused by lesser porosity [5]. Cryogenic treatment (CTT) has drawn the attention of researchers in maximizing the mechanical and tribological behaviour of materials. Pagidipalli et al. [6] analyzed the outcome of DCT on the wear behaviour of different Al–Si Alloys. Volker Franco Steier et al. [7] assessed the effect of a DCT on the wear resistance of Al alloy. The results illustrated that cryogenic treatment enhanced the wear behaviour of the Al alloy. Podgornik et al. [8] analyzed the impact of DCT process such as treatment duration and temperature with plasma nitriding on the wear behaviour of PMHS (Powder Metallurgy High Speed Steel). It was found that finer martensitic structure enhanced the hardness in addition to wear resistance of the material.

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* Correspondence Author

D. Prasanna Venkatesh*, Research Scholar, Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore - 641021, India.Email: prasanna.srmist@gmail.com

P. Shanmughasundaram*, Professor,(2)Department of Automobile Engineering, Karpagam Academy of Higher Education, Coimbatore - 641021, India. Email: sunramlec@rediffmail.com

Lulay et al. [9] analyzed the impact of CTT on 7075 aluminum alloy. Jiang et al. [10] observed favorable effects of cryogenic treatment on the nonferrous metal---aluminium. Rao et al. [11] analyzed the mechanical behavior of Al 6061 alloys that are produced by forging at the temperature of liquid nitrogen. Woodcraft and Adam [12] found considerable enhancement of the strength,hardness and toughness of Al alloy when it was subjected to cryogenic treatment. Elango et al. [13] studied the micro hardness of LM25 - SiC Composite. Other researchers too have carried out studies on the cryogenic treatment [14-16]. From the literature review, it is understood that there is no apparent understanding about the contribution of cryogenic soaking period on the wear loss of the composite materials.

The prime aim of this study is to fabricate MMCs employing squeeze casting method and to establish a relationship between the cryogenic soaking period and their dry sliding wear behavior. Hence, this work aims to find the impact of the war factors on the wear resistance of the LM25- 10% fly ash composite under three different cryogenic soaking periods (0hrs, 12hrs, 24hrs) and three different load and sliding velocities employing wear and friction test rig. The significance of the chosen parameters was analyzed by using Taguchi's technique and Analysis of Variance.

II.MATERIALS AND METHODOLOGY

A. Materials

Al alloy LM25 was chosen as the base material and fly ash (100 microns) as the reinforcement. The chemical composition of LM25 aluminium alloy is given in table1.

Table- 1: Chemical Composition of LM25 Aluminium Alloy

Element	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Sn	Pb	Al
Wt %	6.5	0.4	0.1	0.2	0.05	0.09	0.06	0.012	0.01	0.1	Rest

Fly ash is a residue generated during the burning of coal and recovered from flue gas in thermal plants. It is a mixture of silica (SiO_2), Al_2O_3, Fe_2O_3 and lime (CaO) as main components and oxides of Mg, Na and K as minor components. They are spherical in shape, ranging from 1 µm to 100 µm. The composition of the F type fly ash material with reference to ASTM C618 is given in Table 2.

Table- 2: Chemical Composition of Class F Fly ash

Sl. No.	Componenets	Class F
1.	SiO_2 , Al_2O_3 , Fe_2O_3	70.0
2.	SO_3	5.0
3.	Moisture	3.0
4.	loss of ignition	6.0

Fly ash is classified into percipitator fly ash and cenosphere fly ash. Percipitator fly ash is spherical in nature and the spheres are solids with density in the range between 2.0 and 2.5 gm/cm^3. Cenosphere is also spherical, but the spheres are hollow with density in the range between 0.3 and 0.6 gm/cm^3.

B. Squeeze Casting Process

Composites were made-up through modified two step stir and squeeze casting method, which has advantages of both stir casting and gravity die casting. Squeeze casting which is shown in Fig.1 eliminates the shrinkage and gas porosities and a near net-shaped high dimensional accuracy can be obtained

Fig. 1. Schematic of Squeeze casting setup

C. Cryogenic treatment

Test specimens of LM25 aluminum alloy, LM25+5% fly ash and LM25+10% fly ash composites were subjected to DCT. It was carried out by placing the samples in a liquid nitrogen cryogenic chamber as shown in figure 2 for two different lengths of time: Untreated (0 h), 12hr and 24hr. Cryogenic treatment was performed to assess the soaking effects on the mechanical behaviour of the materials. No post processing was done after the cryogenic treatment. Figure 2 shows the cryogenic liquid storage tank andFigure 3 the processing chamber where the work piece is soaked in liquid nitrogen at -196 °C.

Fig. 2. Storage tank

Fig. 3.Processing chamber

D. Micro structural Examination

In order to observe the microstructure change, standard metallography was used to perform microscopic examination. Microstructures of the LM 25 alloy before and after the deep cryogenic treatment are shown in figure 4 and 5 respectively at 500X magnification. It can be seen from Fig.4 that the grains of untreated specimen are finer. In figure 5 a lot of irregularities are seen on the surface of the deep cryogenic treated specimen, which impedes the slipping system move and cause hardness to increase and elongation decrease.

Fig. 4. Microstructure of the LM 25 alloy before deep cryogenic treatment

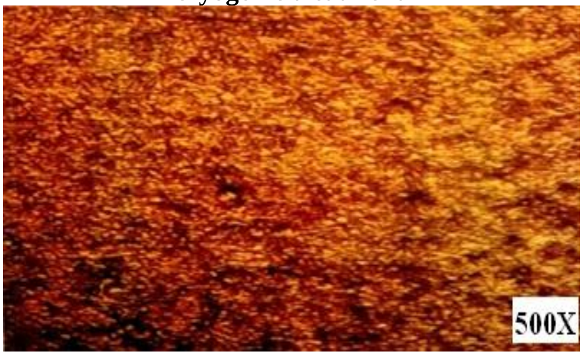


Fig. 5. Microstructure of the LM 25 alloy after deep cryogenic treatment

E. Dry Sliding Wear Test

The wear tests were performed under three different loads and sliding velocities by pin-on-disc wear testing rig as displayed in Fig.6.

Test rig specifications are provided in table.3. The main components of the test rig are variable speed electric motor and carbon counter disc (material EN 31,60HRC). The wear was measured through the linear variable differential transducer (LVDT) in terms of microns (accuracy 1.0 μm). A Pin specimen of 10 mm dia and 30 mm height was prepared. Initially, the pin surface was polished using 500 grit size SiC paper and its surface roughness was measured as Ra= 0.02µm with the help of Mitutoya surface roughness tester (SJ-210). Tests were carried out at a temperature of 27°C and humidity of 55%. Wear values were taken at the end of the 20th minute. The data are assessed using Lab view based software of national instruments “MAGVIEW DATA ACQUISITION SOFTWARE. Schematic of Pin Disc Friction and Wear Test Rig -Controller is shown in Fig.7.

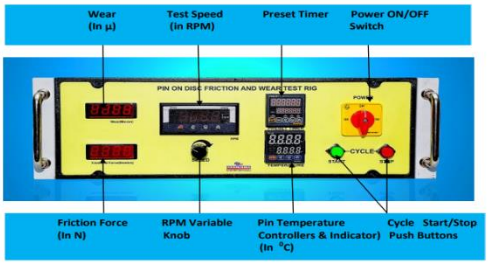


Fig. 7. Schematic of pin-on-disc friction and wear testing rig - Controller

Fig. 6. Schematic of pin-on-disc friction and wear testing rig

Table- 3: Specifications of Pin Disc Friction and Wear Test Rig

1. Normal load range - Up to 200N
2. Frictional Force Range - Up to 200N with a resolution of 1N with tare facility
3. Wear measurement range -+/- 2mm with a tare facility
4. Sliding speed -0.26 to 12 m/s
5. Disc speed- 100 to 2000 rpm
6. Preset timer range – Up to 99 hrs :59mim: 50 sec
7. Wear Disc Diameter - 165 mm, Thk-8mm (EN31 disc 58-60HRC)
8. Wear Disc Track Diameter – 10mm to 140mm
9. Specimen Pin diameter /Diagonal- 3 mm to 12 mm
10. Pin length – 25 mm to 30 mm
11. Data Acquisition System- Up to 8 Channels with National Instruments USB DAQ Card
12. Pin Heating System- up to 250 °C
13. Lubricating Re- Circulating System
14. Specimen Holders- Ball, Square, Rectangular

III.TAGUCHI METHOD AND ANALYSIS OF VARIANCE (ANOVA)

The Taguchi method is adopted to observe the influencing wear resistance of the material. “Lower is better” S/N (Signal to Noise) ratio is chosen to find the optimal level of factors as a lower wear was required.Statistical equation of the S/N ratio is specified in the equation (i).

$$\frac{S}{N} = -10 \log\left(\frac{1}{n}\sum_i \frac{1}{y_i^2}\right) \qquad \text{Eq. 1}$$

Where, y is the measured data and n the number of tests.

The wear parameters, each at three levels, were considered and the details are presented in Table 4. Taguchi and ANOVA analysis were made using MINITAB15.

Obtained values and the corresponding S/N ratios for wear loss are given in table 5. Additionally, the importance of the factors that have influenced the outcome was analyzed and the contribution of the parameters in terms of percentage at 95% confidence level using ANOVA. The F (Fisher) ratio was used to identify which parameters had major effect on the outcome of the process. Furthermore, the percentage contribution shows the degree of influence of the parameters for the response.

Table- 4: Parameters and levels

Level	Load, N (A)	Sliding Velocity, m/s (B)	Cryogenic Soaking period (hr) (C)
I	10	1	0
II	20	1.5	12
III	30	2	24

Table- 5: Measured values and S/N ratios for wear loss

Exp. No	Load ,N (A)	Sliding Velocity, m/s (B)	Cryogenic Soaking period (hr) (C)	Wear Loss (µm)	S/N ratio
1	10	1	0	130	-42.2789
2	10	1.5	12	120	-41.5836
3	10	2	24	117	-41.3637
4	20	1	12	136	-42.6708
5	20	1.5	24	131	-42.3454
6	20	2	0	169	-44.5577
7	30	1	24	146	-43.2871
8	30	1.5	0	184	-45.2964
9	30	2	12	165	-44.3497

IV.RESULTS AND DISCUSSION

A. Results of S/N Ratio

Signal to Noise Ratios for wear loss is given in table 6, which reveals that the load is the dominant parameter followed by cryogenic soaking period and velocity for the wear loss of LM25-10% fly ash composites.

Table- 6: Response table for Signal to Noise Ratios for wear loss of the materials

Level	A- Load	Sliding Velocity (B)	C-Cryogenic Soaking period (hrs.)
1	-41.74	-42.75	-44.04
2	-43.19	-43.08	-42.87
3	-44.31	-43.42	-42.33
Delta	2.57	0.68	1.71
Rank	1	3	2

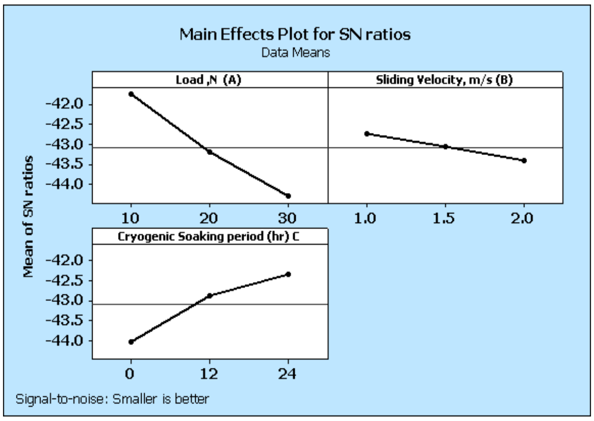


Fig. 8. Response diagram of S/N ratio for wear loss of Al alloy – Fly ash composites

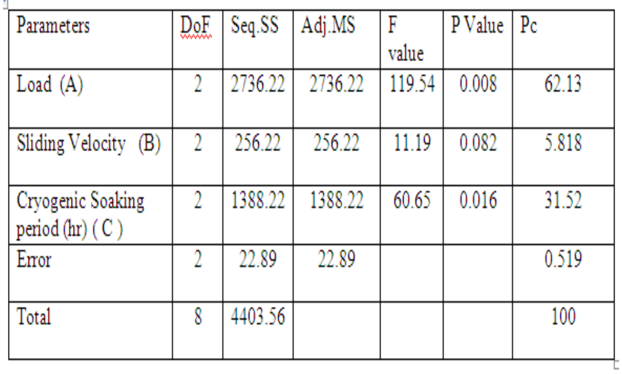
The optimal levels of parameters were found to be load (30N), sliding velocity (1m/s) and cryogenic soaking period (24 hrs) for the wear loss of the LM25-10% fly ash MMCs.

B. Results of ANOVA

ANOVA analysis for wear resistance was carried out, and the resulting data are given in Table 7. The P (probability) value shows that the considered process parameters are highly significant parameters affecting the wear of the material. It can be noted that load has the most contributing parameter on the wear resistance of the material as shown by much higher F-value (i.e., 119.54) and contribution (i.e., 62.13 %) followed by cryogenic soaking period (hr) and sliding velocity.

If the value of P is below 0.05, then the factor is deemed to be statistically important. It can be inferred from table 7 that the load (62.13%) is the major contributing parameter followed by cryogenic soaking period (31.52%) and sliding velocity (5.818%).

Table- 7: ANOVA analysis for wear loss of LM25-10% fly ash composites



Parameters	DoF	Seq.SS	Adj.MS	F value	P Value	Pc
Load (A)	2	2736.22	2736.22	119.54	0.008	62.13
Sliding Velocity (B)	2	256.22	256.22	11.19	0.082	5.818
Cryogenic Soaking period (hr) (C)	2	1388.22	1388.22	60.65	0.016	31.52
Error	2	22.89	22.89			0.519
Total	8	4403.56				100

C. Multiple Linear Regression Model

The regression coefficient, R^2 (0.9948) is almost equal to the adjusted R^2 (0.9792). Hence the wear data are not scattered.

The equation generated for wear loss of the material is

Ra= 96.9+2.13 (A) + 13.0 (B) - 1.24 C Eq. 2

Where Ra = is wear loss, A- Load, B- Sliding velocity and C- Cryogenic soaking period.

Eq.2 shows that the coefficient correlated with load (A) and sliding velocity (B) is positive.

D. Confirmation Test

The confirmation experiment results are given in table 8 and table 9 respectively. Figure 9 shows the typical curve of wear of LM25-10% fly ash composite as a function of sliding velocity (1.5m/s), applied load (30N) and cryogenic soaking period (24hrs).

Table- 8:Parameters used in the confirmation test

Load (A)	Sliding Velocity (B)	Cryogenic Soaking period (hr.) (C)
30	1.5	24

Table-9: Result of confirmation test

Model equation	Expt.	Error (%)
150.54	155	2.96

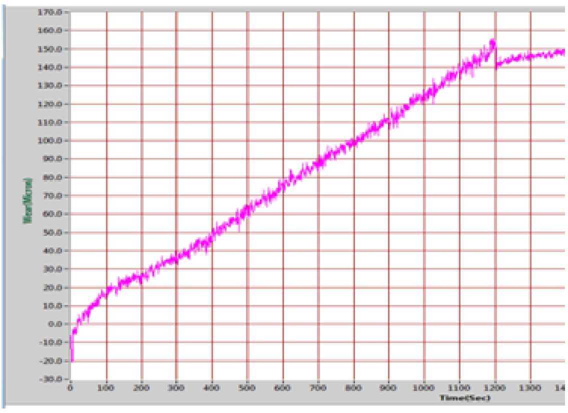


Fig. 9. Typical curve of wear of LM25-10% fly ash compositeas a function of sliding velocity (1.5m/s), applied load (30N) and cryogenic soaking period (24hrs)

V.WEAR LOSS OF LM25-10% FLY ASH COMPOSITES

Fig. 10.Wear loss of LM25-10% fly ash composites

Figure 10 illustrates the wear loss of LM25 - 10% fly ash composites under three different loads (10N, 20N and 30N) and two different velocities (1m/s, 2m/s). The wear loss of the composite increased from 110µm to 146µm when the load was raised from 10 N to 30 N at a velocity of 1m/s and cryogenic soaking period of 24hrs. As the load increased the wear loss tended to increase irrespective of the velocity and cryogenic soaking.

The wear loss of the composite decreased from 177µm to 146µm when the cryogenic soaking period was increased from 0 hrs to 24 hrs at a velocity of 1m/s and load of 30N. Wear loss of the material decreased by 17.5%. It can be inferred that as cryogenic soaking period increases, the wear resistance increases. However, when the soaking period was increased form 12 hrs to 24 hrs, a slight enhancement in wear resistance was noted. The wear loss of the composite decreased from 165µm to 152µm when the cryogenic soaking period was increased from 12 hrs to 24 hrs at a velocity of 2m/s and load of 30N. Wear loss of the material decreased by 7.87%. Conversely, the wear loss of LM25-10% fly ash composites inreased from 146µm to 152µm as the velocity was raised from 1m/s to 2m/s at a constant load of 30N and cryogenic soaking period of 24hrs. As the sliding velocity rose, the wear resistance decreased monotonically.

A. Effect of the Load on the wear resistance

The obtained values of wear loss (µm) was plotted for 3 different loads keeping the other two parameters such as sliding velocity (1 m/s) and cryogenic soaking period (24 hrs) as constants at their optimum levels. The optimum level of load was 10N. Figure. 11 portrays that the wear resistance declines when the load increases. The wear loss increases from 110µm to 146µm by 32.72 % when the load is raised from 10N to 30N.

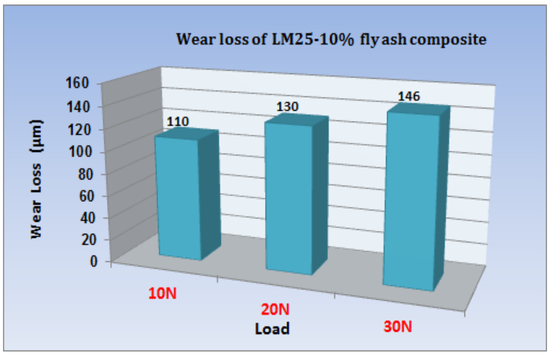


Fig. 11.Effect Of Load On The Wear Resistance

B. Effect of the sliding velocity on the wear resistance

Wear loss values were plotted for 3 different sliding velocities by keeping the optimum load 10N and cryogenic soaking period (24hr). Figure 12 illustrates that the wear of the material increases with velocity.

The results reveal that the wear loss increases from 110µm to 117µm 6.36 % by 19% while the velocity is raised from 1 m/s to 3 m/s at a load of 10N and cryogenic soaking period (24hrs).

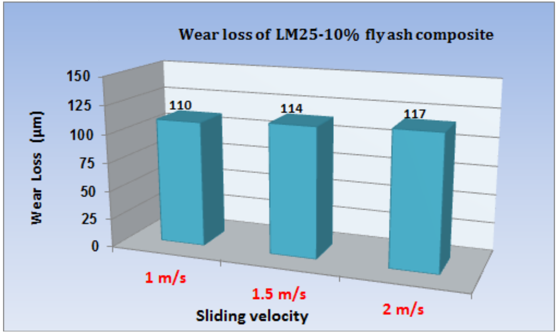


Fig. 12.Effect of sliding velocity on the wear resistance

C. Effect of the cryogenic soaking period on the wear resistance

Wear loss of the materials against the cryogenic soaking period at an invariable velocity of 1m/s and a constant load of 10 N is presented in Figure 13. It shows that as cryogenic soaking period rises, the wear resistance of the material tends to increase. Wear loss decreases from 130 µm to 110 µm when cryogenic soaking period is increased from 0hrs to 24hrs. A considerable drop (15.38%) in wear loss is attained by increasing the cryogenic soaking period.

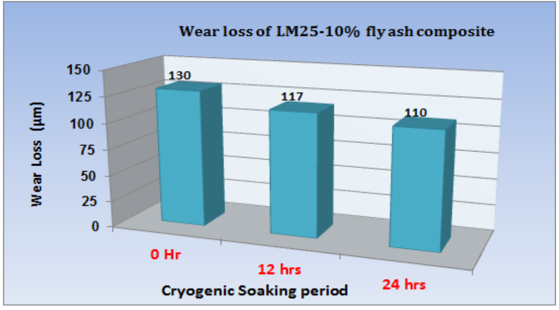


Fig. 13.Effect Of Cryogenic Soaking Period On The Wear Resistance

VI.CONCLUSIONS

Wear resistance of the composites was investigated. The load was the key factor followed by cryogenic soaking period and sliding velocity. Results illustrated that wear of the materials increased with increase in load, sliding velocity and cryogenic soaking period. The lowest wear loss values occurred at the lowest load and the higher cryogenic soaking period. The outcomes of investigation demonstrated that the load (62.13%) was the major parameter apart from cryogenic soaking period (31.52%) and sliding velocity (5.818%) on the wear resistance of the LM25-10% fly ash composites. The wear loss decreased with increasing cryogenic soaking period. Resulted modeling equation can be used to envisage the wear loss of the materials within the observed range.

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AUTHORS PROFILE

D. PrasannaVenkatesh, Phd Research Scholar, Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore - 641021, India.

Dr.P.Shanmughasundaram born in Kalangal, Coimbatore, Tamilnadu, India, received his A.M.I.E (India) degree in Mechanical Engineering and A.M.I.E (India) degree in Production Engineering from Institution of Engineers (India). He received Master’s Degree M.E (Refrigeration and Air conditioning) from Coimbatore Institute of Technology, India. He obtained Doctoral degree in the Mechanical Engineering from PSG College of Technology, Anna University, Chennai. He has an experience of about 20 years in teaching various subjects of Mechanical and Automobile Engineering. He has produced 5 PhDs and he is guiding 8 PhD scholars. To his credit, he has 60 International peer reviewed Scopus and SCI Journal publications. He has authored a book chapter in Elsevier publication. He is the reviewer of more than 25 Scopus and SCI International Journals. His areas of interest are Metal Matrix Composites, Tribology and Optimization techniques. He has organized 1 International Conference, 6 National conferences and 15 National level workshops. He is a member of Society of Automotive Engineers (SAE), Fellow of Institution of Engineers (India), life member of Indian Society for Technical Education and Tribology Society of India.