Evaluation of Mechanical Properties and Wear Behavior of Aluminium-Red Mud Composite Synthesized By Powder Metallurgy

Neelima Devi Chinta,[a,*] N. Selvaraj,[b] and V. Mahesh[c]

[a)]Department of ME, University College of Engineering, JNTUK, Vizianagaram -535003, India.
[b)]Department of ME, National Institute of Technology, Warangal - 506004, India.
c)Department of ME, S.R Engineering College, Warangal - 506371, India.

*Corresponding author:Neelima Devi Chinta, Email: cneelima.me@jntukucev.ac.in

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ABSTRACT

Red mud received from NALCO, Odisha, India has been subjected for sieve analysis and milled to 42 nanometers using high energy ball mill. Pure aluminium powder of 99.72% purity as matrix with red mud as reinforcement at 2%, 4%, and 6% weight fractions at micro as well as nano levels. Micro and nano structured red mud powders and pure aluminium are mixed in a V-blender, compacted at a pressure of 40 bar and samples are prepared by conventional sintering. The mechanical properties of Aluminium-Red mud micro and nano composites are evaluated with respect to hardness and compression strength. The experimental compression strength values are validated by Deform-2D software. An increase in hardness and compression strength is observed with increase in the amount of percentage weight fraction of Red mud. Wear characteristics are investigated using pin-on-disc wear testing machine and evaluated the prediction of optimal combination of pure aluminium and weight fraction of micro and nano structured red mud powder using Regression analysis. Highest wear resistance is observed for the test specimen with 42 nm size and 6% weight fraction of red mud powder at 600 RPM speed.

KEY WORDS: *Nanocomposites; Sintering and Mechanical Properties.*

NOMENCLATURE

Al	Aluminium
RM	Red mud
Φ	Diameter
%	Percentage

1.0 INTRODUCTION

Red mud is an industrial solid waste which is known as bauxite residue obtained during the processing of alumina by Bayer's process. An attempt has been made to utilize this solid waste using as the reinforcement material in Metal Matrix Composites (MMCs) and Metal Matrix Nano Composites (MMNCs). A lot of difficulty is being experienced by the manufacturing industries to dispose their wastage and utilize their byproducts. The Bauxite residue which is known as Red mud is mixed with other metals mainly to aluminum to form metal matrix composites which exhibit superior mechanical properties and applications [1, 2]. Powder compaction is the process of compacting metal powder in a die through the application of high pressures. The powder is compacted into a shape using the punch tool held in vertical orientation and then ejected from the die cavity. Hazardous industrial, electronic, and bio medical wastes lead to burden on the earth [3, 4]. Hence waste treatment is one of the top most problems of the world. Red mud has been used in the removal of Sulphur compounds from kerosene oil [5, 6], in the heap leaching of gold ores as a pH modifier [7, 8], in the anthracene hydrogenation [9, 10] and as a pigment in marine paints as anticorrosive [11, 12, 13].

In China, approximately 10% of Red mud produced is recycled for further metal extraction or utilized as a raw material for brick production [14]. In India, it is reported that 2.5 million tons are absorbed by the cement industry. Residual Bauxite was introduced as a raw material along with other raw materials such as lime, clay, silica etc. The tests confirmed that residue added cement, as well as mortar and concrete made from this cement, meet the Japanese Industrial Standards [15].

2.0 EXPERIMENTAL SET UP

2.1 Sieve analysis

Sieve analysis (or gradation test) is a procedure used to assess the particle size distribution of a granular material. It is also called as particle sizing technique. The red mud used for the present investigation is collected from the National Aluminum Company Limited (NALCO) Damanjodi, Odisha, India. The Chemical compositions of Red mud and Pure Aluminium powder of 99.72% purity are shown in Table 1 and 2 respectively.

Table 1: Chemical composition of Red mud

Fe_2O_3	Al_2O_3	TiO_2	SiO_2	Na_2O	CaO	V_2O_5	Others
53.8	14.3	3.9	8.34	4.3	2.5	0.38	Balance

Table 2: Chemical composition of Pure Aluminium

Element	Fe	Si	Mg	Mn	Cu	Zn
Wt%	0.17	0.07	0.001	0.0008	0.005	0.003

As-received Red mud is subjected to sieve analysis using mechanical sieve shaker for collecting particles of uniform sizes of 100, 150, and 200 microns for preparing the micro sized Red mud powder.

2.2 High Energy Ball Milling

Nano particles are formed in a mechanical device known as high energy ball mill referred to as Pulverisette for conducting mechanical attrition experiments. The reduction in particle size of Red mud from micron level to the nano level is carried out using a high-energy planetary ball mill in a stainless steel chamber using tungsten carbide of 10 mm Φ size. The micron sized Red mud powder is milled for 30 hours by maintaining the rotation speed of the planet carrier at 200 rpm. The ball mill is loaded with ball to powder weight ratio (BPR) of 10:1. Toluene is used as the medium with an anionic surface active agent to avoid agglomeration. The milled sample powder is taken out after 6 hours, 13 hours, 24 hours and 30 hours of milling and dried with mechanical drier. The XRD Pattern for 30 hours milled Red mud is shown in figure 1.

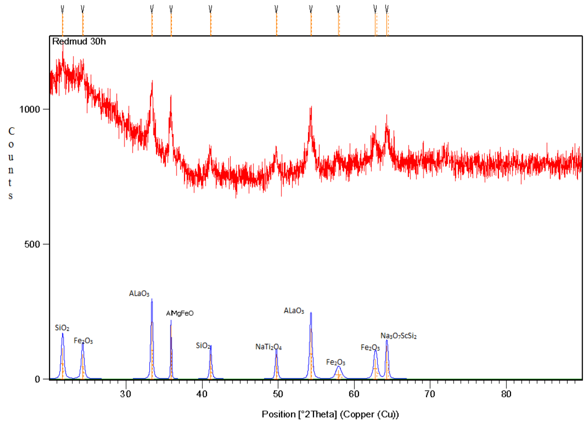

Figure 1: XRD Pattern for 30 hours milled Red mud.

The crystallite size is reduced from 400 nm to 42 nm during 30 hours of ball milling. The fresh Red mud powder particles are mostly angular in shape. The shapes of the 30 hours milled particles are irregular and the surface morphology is rough. The relative lattice strain is increasing with increasing the duration of milling time. This lattice strain is increased from 0.12 to 0.28 for as-received Red mud powder after 30 hours of milling. The intensity of the peaks in the XRD pattern got reduced and the peak broadening increased as the duration of milling time increases.

2.3 Mixing and Compacting

The micro level Red mud powders of 100, 150 and 200 microns and nano level Red mud powder of 42 nm (or 0.042 microns) at 2%, 4% and 6% of weight fractions are mixed with Pure Aluminium powder in a double cone mixer for 10 hours in order to obtain proper interaction of particles with each other. The different proportions of Al-Red mud sample materials are compacted in a hydraulic press of 100 ton load capacity and 7.5 H.P. During compacting pressure applied was 40 bar and compact pressing time was 4 sec.

2.4 Sintering

Sintering is a thermal treatment, below the melting temperature of the main constituent material, which transforms a metallic or ceramic powder (or a powder compact) into a bulk material. The Vacuum maintained during sintering was 250 Pa (using a compressor of 1.5 H.P) and raising the temperature to 300^0C in 30 minutes soaking at 300^0C for 30 minutes. Then raising the temperature to 620^0C(time taken is 35minutes) and again soaking at 620^0C for 30 minutes. Then cooling is done to room temperature (time taken is about 3hrs). Hence the total sintering cycle time was 5hours 5minutes.

Figure 2: Compacted Pure Aluminium and Red mud samples in Sintering Machine.

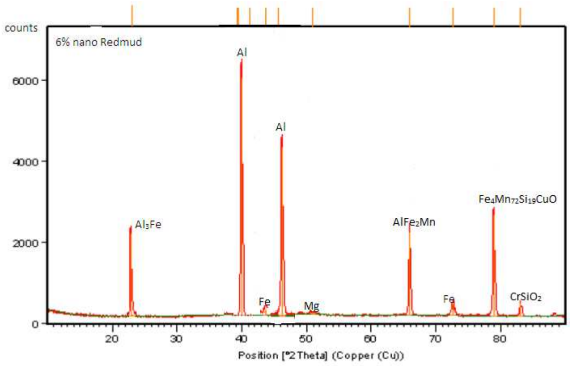

Figure 3: XRD pattern for Pure Aluminium and 6% nano Red mud compacted sample after Sintering.

Table 3: Hardness values for Aluminium with Redmud samples

S.No	Specimen composition	Vickers Hardness Number
1	Pure Al (99.72% purity)	47.4
2	Al with 2% Red mud (100 microns)	60.2
3	Al with 4% Red mud (100 microns)	67.6
,	Al with 6% Red mud (100 microns)	74.5
5	Al with 2% Red mud (150 microns)	58.3
6	Al with 4% Red mud (150 microns)	62.4
7	Al with 6% Red mud (150 microns)	69.2
8	Al with 2% Red mud (200 microns)	56.7
9	Al with 4% Red mud (200 microns)	59.3
10	Al with 6% Red mud (200 microns)	63.5
11	Al with 2% Red mud(0.042 microns)	73.6
12	Al with 4% Red mud(0.042 microns)	77.4
13	Al with 6% Red mud (0.042microns)	83.9

The figure 2 shows the Aluminium and Red mud compacted samples in Sintering Machine of vacuum chamber. The Vacuum sinter furnace is manufactured by ACME (Advanced Corporation for Materials and Equipments), China. The Model No. ZSJ-25x25x50 with loaded weight of 50 kg and loaded vacuum of $4x10^{-3}$ Pa. The raised sintering furnace temperature upto 1550^0C with heating power capacity of 50kW. The Figure 3 shows the X-Ray Diffraction (XRD) pattern for Pure Aluminium and 6% nano Red mud compacted sample which has Al-Al_3Fe phase and many other compounds like $AlFe_2Mn$, $Fe_4Mn_{72}Si_{19}CuO$, Mg after Sintering. This confirms the presence of Red mud in the pure Aluminium powder based nano metal matrix composite. There are nine peaks have been obtainted in the 2θ span ranging from 10 to 100. The micro Vickers Hardness values for pure Aluminium and Aluminium with Redmud are shown in Table 3.

3.0 RESULTS AND DISCUSSIONS

3.1 Hardness and Compressive strength

Hardness values are measured using Micro Vickers Hardness tester. The graph between Hardness and % weight fraction of Red mud is shown in figure 4. Aluminium is a ductile material, addition of small amount of reinforcement material to it will gives strength but not change its ductility so compression strength at 10, 20, and 30 percent reduction is determined. Using Compression Testing machine Compression Strength values are calculated experimentally and validated using Deform-2D software.

The figure 5 shows compressive stress for 100 microns with particle size of 6% weight fraction of Red mud with Pure Aluminium at 10% reduction using Deform-2D software. Both experimental and Deform-2D simulated compressive stress values are shown in Table 4 and Table 5 respectively.

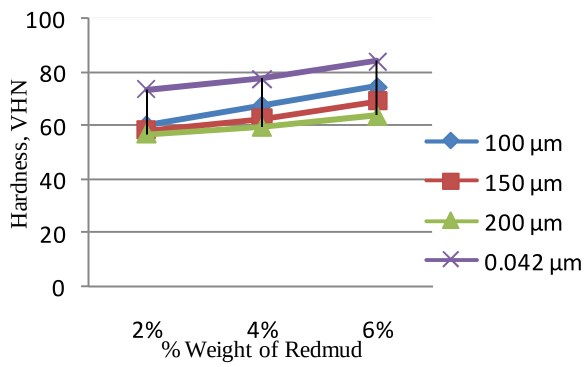

Figure 4: Plot between Hardness and % Weight fraction of Red mud.

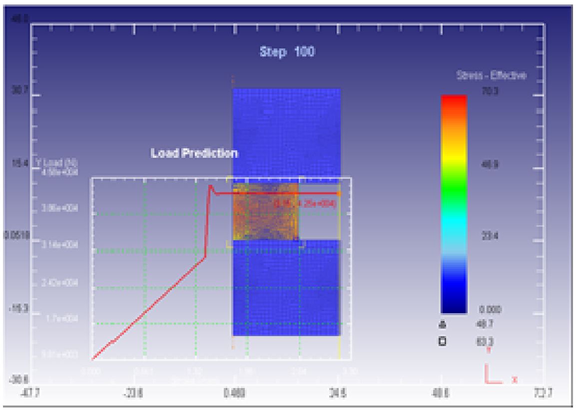

Figure 5: Compressive Stress for Pure Aluminium with 6% weight fraction of Red mud of 100 microns size at 10% reduction.

Table 4: Experimental results of Compressive Strength from Deform-2D software

S.No	%Wt of Red mud	Particle size μm	Stress at 10% reduction MPa	Stress at 20% reduction MPa	Stress at 30% reduction MPa
1	Pure Aluminium	45	53.7	70.7	79.5
2	Aluminium + 2%RM	100	48.9	75.2	81.5
3	Aluminium +2% RM	0.042	49.9	77.1	82.4
4	Aluminium +4% RM	100	51.4	80.8	87.8
5	Aluminium +4% RM	0.042	62.3	76.4	89.6
6	Aluminium +6% RM	100	70.3	89.7	94.6
7	Aluminium +6% RM	0.042	58.2	92.1	98.4

Hardness and Compression Strength values are depicted the information that Nano Red mud specimens have more hardness and compression strength when compared with micro nature specimens. As % weight fraction composition of Red mud increases, hardness and Compression Strength values are also increases. This is due to the ferrous materials are harder in nature. Since the Red mud consists of ferrous oxide as its major constituent about 53.8%. Hence this justifies the observation that as the percentage weight fraction of Red mud increases, the hardness and compression strength of the total composite are also increases. Since finer particles are strongly bonded with each other in a composite, the hardness and compression strength values of the nano composites are higher when compared to the micro level.

Table: 5 Simulated results of Compressive Strength from Deform-2D software

S.No	%Wt of Red mud	Particle size μm	Stress at 10% reduction MPa	Stress at 20% reduction MPa	Stress at 30% reduction MPa
1	Pure Aluminium	45	49.81	66.71	75.33
2	Aluminium + 2%RM	100	44.59	71.67	78.21
3	Aluminium +2% RM	0.042	46.12	72.95	79.57
4	Aluminium +4% RM	100	47.84	75.94	83.45
5	Aluminium +4% RM	0.042	59.36	74.21	86.42
6	Aluminium +6% RM	100	68.65	85.98	91.24
7	Aluminium +6% RM	0.042	54.95	89.54	95.74

3.2 Wear Rate

Experiments have been conducted on the Pin-on-disc Wear Testing machine with data acquisition system, which is used to evaluate the wear behavior of the composite, against hardened ground steel disc (En-32) having hardness 65 HRC and surface roughness (Ra) 0.5 µm. This equipment designed to study wear rate under sliding condition only. Sliding generally occurs between a stationary Pin and a rotating disc. The disc rotates with the help of a D.C. motor having speed range 0-1000 rpm with wear track diameter 50 mm-80 mm, which could yield sliding speed 0 to 10 m/sec. Load of 10N is to be applied on pin (specimen) by dead weight through pulley string arrangement. The wear tests are performed as per standards of ASTM G-99 with unlubricated condition in a normal laboratory atmosphere at 55% relative humidity and a temperature of 27-31ºC. Each Aluminium-Red mud composite samples are conducted for 6 hours. The samples are cleaned with the solution of tetra chloro ethylene before and after the wear test. In Table 6, the experimental wear rate results at 200, 400 and 600 rpm are shown.

From the figure 6 to figure 8 the results of Wear Rate Vs % Weight fraction of Red mud at 200, 400 and 600 rpm are plotted. The Red mud constituents (Ferrous oxide) are harder in nature, the percentage weight fraction of the red mud increases the wear resistance of the whole composite also increases. The maximum wear resistance is obtained for 42 nm or 0.042 microns level of 6% weight fraction of Red mud with Pure Aluminium.

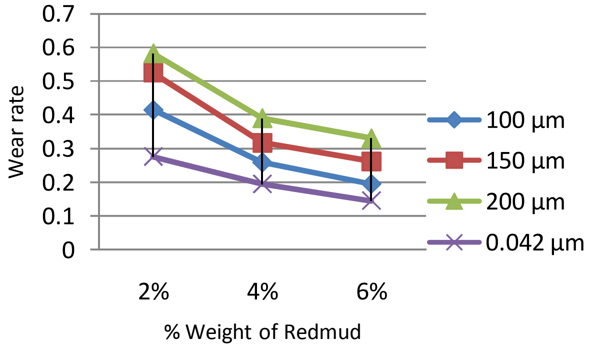

Figure 6: Plot between Wear Rate Vs %Weight fraction of Red mud at 200 rpm.

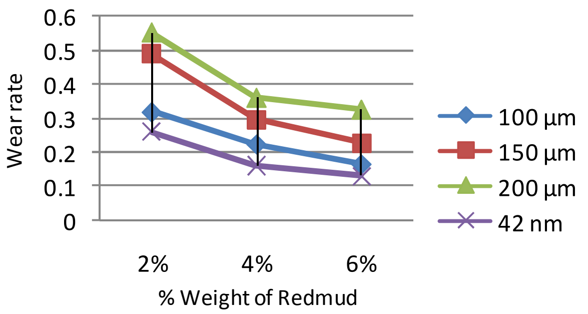

Figure 7: Plot between Wear Rate Vs % Weight fraction of Red mud at 400 rpm.

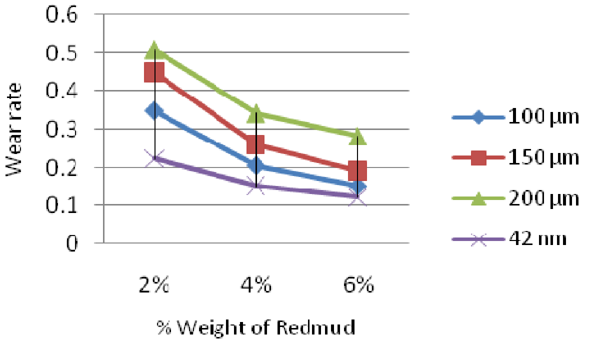

Figure 8: Plot between Wear Rate Vs % Weight fraction of Red mud at 600 rpm.

3.3 Mathematical Prediction

A mathematical model is developed and the overall equation is obtained using Regression analysis which is shown in equation 1. The multiple R value is 0.9554 and obtained standard error is 0.03928. The Overall equation is stated as below.

Wear rate = 0.434552+ [(0.001107) x particle size] - [(0.0519) x percentage Weight fraction of Red mud] - [(0.00013) x speed] (1)

Table 6: Experimental Results of Wear Rate from Pin-on-disc Wear Testing machine

S.No	Particle Size Microns	Wt % of Red mud gm	Speed RPM	Wear rate $X10^{-6}$N/m
1	100	2	200	0.415
2	150	2	200	0.524
3	200	2	200	0.582
4	0.042	2	200	0.276
5	100	4	200	0.259
6	150	4	200	0.317
7	200	4	200	0.39
8	0.042	4	200	0.195
9	100	6	200	0.195
10	150	6	200	0.262
11	200	6	200	0.33
12	0.042	6	200	0.145
13	100	2	400	0.391
14	150	2	400	0.488
15	200	2	400	0.553
16	0.042	2	400	0.259
17	100	4	400	0.224
18	150	4	400	0.295
19	200	4	400	0.36
20	0.042	4	400	0.162
21	100	6	400	0.165
22	150	6	400	0.228
23	200	6	400	0.325
24	0.042	6	400	0.131
25	100	2	600	0.35
26	150	2	600	0.45
27	200	2	600	0.51
28	0.042	2	600	0.223
29	100	4	600	0.207
30	150	4	600	0.261
31	200	4	600	0.342
32	0.042	4	600	0.152
33	100	6	600	0.153
34	150	6	600	0.192
35	200	6	600	0.282
36	0.042	6	600	0.122

The value of R square is 0.9128 and is very near to the unity i.e the relation between the weight percentageof red mud and the wear rate is linear, so the in between values can calculate with maximum accuratly.

4.0 CONCLUSION

An increase in hardness and compression strength is observed with increase in the amount of percentage weight fraction of Red mud. It is also observed that, for the same percentage weight fraction of Red mud, the hardness and compression strength are higher for the nano structured reinforcement than micro structured reinforcement. This is due to the increase in surface area of contact and higher bond strengths. Hardness and compression strength properties are improved for nano level

Aluminium-Red mud test specimen with 42 nm size and 6% weight fraction of Red mud. The Simulated results of Compression Strength using Deform-2D software and experimental values are within the limits of 2-5% difference. As increase in speed of rotation of the specimen, the wear resistance is higher. Highest wear resistance is observed for the test specimen with 42 nm size and 6% weight fraction of Red mud powder at 600 RPM speed.

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