Taguchi analysis for sliding wear characteristics of carbon nanotube-flyash reinforced aluminium nanocomposites

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ABSTRACT

Dry sliding wear characteristics of aluminium nano-composites reinforced with different wt. % of multiwall carbon nanotubes (0.25, 0.5, 0.75 wt. %) and fly ash (4, 8, 16 wt. %) produced by powder metallurgy were investigated. ANOVA and Taguchi methods of design of experiment technique were successfully used to determine the predominant factors and optimisation of the testing parameters on wear. MWCNT (wt. %) and FA (wt. %) was found to be the predominant parameter affecting wear loss with percentage contribution of 43.71% and 30.78%. The results of Taguchi indicate the optimized values of wear parameters were 0.25wt. % MWCNT, 8 wt. % FA, 2 h ball milling, 6 h sintering, 10 N applied load, 200 rpm sliding speed and 500 m sliding distance. The microstructure of composites exhibited well dispersion of the reinforcements in the aluminium matrix. The study of worn surfaces revealed minor grooves and delamination wear due to abrasive and adhesive wear mechanisms.

1. Introduction

Metal matrix composites (MMCs) have more advantages over pure metals or alloys in terms of high specific modulus, specific strength, creep, corrosion and wear resistance properties [1, 2, 3]. Out of several metal matrixes employed to fabricate MMCs, aluminium (Al) metal has been widely accepted matrix because of its low density, good thermal conductivity and high corrosion resistance properties and is widely used for the consumption in the aerospace and automotive industries [4]. Many ceramic reinforcements such as silicon carbide, aluminium oxide, zirconium oxide etc. are used in the aluminium metal matrix composites [5]. One essential factor which limits use of these ceramic reinforcements is the high cost of fabrication which can be minimized by using inexpensive reinforcements such as fly ash and natural minerals [6]. Fly ash (FA) is one of the industrial wastes coming out from thermal power plant which is available in large quantities in the Indian subcontinent and all over the world and is suitable for reinforcement material in composites [7]. Many literatures have reported the potentials of the use of flyash as reinforcements. Ramachandra et al. [8] reported that wear resistance property of composites developed with the use of flyash up to 15% have been increased. Marin et al. [9] observed improvement of corrosion resistance property by the inclusion of FA to the pure aluminium metal matrix composites. Hrairi et al. [10] reported that the density of the fly ash reinforced composites decreases with increase in fly ash content. Rohatgi et al. [11] reported that hardness property of composites increased with increase in flyash up to 10 wt. %. Narasimha et al. [12] reported that the addition of nano flyash increases the hardness and compression strength properties of the composites. On the other hand carbon nanotubes (CNTs) as a reinforcement in the fabrication of composites is gaining more importance due to their eminent physical, thermo-mechanical properties (specific strength 55.55 GPa/(mg/m3), specific modulus of 555.55 GPa/(mg/m3)) [13]. Apart from that CNTs also have greater aspect ratio, very good chemical stability and electrical properties. These features of CNTs are advantageous for applications in the aerospace and automotive sectors, where energy conservation has become more critical [14]. One of the big hurdles to the effective use of carbon nanotubes as reinforcements is their agglomeration and poor dispersion in metal matrix. Enhancements in mechanical properties due to CNT addition have been reported. Wang et al. [15] fabricated 2 wt. % MWCNTs (multiwall carbon nanotube) reinforced with aluminium composites by a powder metallurgical method. The results indicated that the hardness was increased from 62.17 HV (12 h ball milling) to 182.8 HV (72-hour ball milling). It was shown that presence of a few small-diameter MWCNTs hinder the formation agglomerates which leads to the improvement of the properties. Deng et al. [16] fabricated 1 wt. % carbon nanotubes reinforced with 2024 Al matrix by cold
compacting and followed by hot extrusion. The hardness, young’s modulus, yield strength and tensile strength of the CNT/Al composites have all been improved by about 30.8%, 23.9%, 16.3% and 23.4% respectively compared to the matrix alloy. Bustamante et al. [17] investigated 2 wt. % MWCNT reinforced aluminium matrix composite fabricated by powder metallurgy technique. The yield strength, maximum strength of the composites have been improved by 100% and 95% respectively compared to pure aluminium matrix. Liu et al. [18] investigated MWCNTs reinforced Al 1016 aluminium matrix composites fabricated by friction stir processing. It was shown that tensile strength and micro hardness of the samples increased while elongation decreased with the increase in reinforcement content. Choi et al. [19] reported that multi wall carbon nanotubes form strong interface by mechanical interlocking with matrix leading to high yield stress (more than 600 MPa) and low coefficient of friction (less than 0.1) in 4.5 vol. % of multi wall carbon nanotubes reinforced Al composites. It was shown that coefficient of friction and the wear rate increased with increase in load while decreased with the increase in sliding speed. Micro ploughing and delamination was considered major wear mechanism in the wear specimens.

Currently, there are several fabrication methods of metal matrix composites (MMCs) under conventional casting and powder metallurgy method [20]. Casting methods for the fabrication of MMCs seriously suffer from limitations such as agglomeration and thermal degradation during processing. The powder metallurgy methods is attractive due to the low processing temperature. That is why undesired phases between the matrix phase and the reinforcement phase are eliminated. In powder metallurgy, powders of metal matrix and reinforcement are homogeneously mixed and then compacted to get the required shape. After compaction sintering is applied to get better mechanical properties. Mechanical milling (also called ball milling) is a useful mixing method in powder metallurgy, performed to get a homogenous mixture of metal matrix and reinforcing material. Ball milling continuously breaks and re-welds the powder grains due to the action of balls and movement of the container. A variety of research groups investigated the use of ball milling as a form of mechanical dispersion technique [16, 17, 18, 19].

The use of design of experiments technique such as Taguchi and ANOVA methods has been widely used method to reduce number of tests (experiments) and deals with outputs that are influenced by multi-variables. It is a promising technique to optimise the process variables and to identify the optimal combination of the variables for a given output. Such an approach has been successfully applied to determine the influential factors on the wear rate of the nano-composites [21, 22, 23, 24]. Babu et al. [21] used Taguchi method to determine the significance of testing factors for GNFs/Al2O3sf (graphite nano-fibre/alumina short fibre) reinforced aluminium hybrid composites. It was shown that sliding distance was the most predominant parameter with percentage contribution of 46% which controls the wear rate compared to other parameters (reinforcement (vol. %), the load applied and sliding speed). The results showed reduced wear loss for the composites reinforced with 15 vol. % reinforcement. Also authors reported that formation of mechanically mixed layer (MML) during the wear process reduces the wear loss. Basavarajappa and Chandramohan [22] applied Taguchi method to determine the significance of process parameters on the wear of Al–Cu–Mg matrix reinforced silicon carbide composites. It was shown that sliding distance was predominant factor with percentage contribution of 49.12% compared to other parameters (load, sliding speed, and reinforcement). Suresh and Sridhara [23] used central composites design (CCD) method to analyse the tribology behaviours of aluminium–silicon carbide–graphite composites produced by stir casting technique. It was shown that 7.5% reinforcement was the optimal reinforcement for any value of sliding distance, sliding speed and load. It was also observed that wear increased with increase of either load or sliding distance or both and decreased with increase of speed. It may be seen from the above discussions that the composites have been studied from different combinations of reinforcements, matrix and process parameters on their wear properties. Therefore, in the present study, wear property of multi-wall carbon

Figure 1. SEM image of (a) Fly-ash (b) Pure aluminium (c) MWCNT.
nanotubes (MWCNT) and fly ash (FA) reinforced with pure aluminium matrix hybrid composites was analysed. Taguchi and ANOVA analysis were carried out to determine the contribution of wear parameters for the low wear property of the fabricated composite under dry sliding wear conditions. The powder morphology, sintered sample and worn surfaces were studied and analysed using scanning electron microscope (SEM).

2. Experimental procedure

Aluminium powder (99.7% pure, 7–50 μm in size), 4, 8 and 16 wt. % fly ash (average diameter - 9.299 μm) and 0.25, 0.5 and 0.75 wt. % multi-wall carbon nanotubes (average dimensions: 10–15 nm outer diameter, 2–6 nm inner diameter and 0.1–10 μm in length, Chengdu chemicals Co.

Figure 2. (a) Pin on disc wear test apparatus (b) Pin on disc wear testing principle.

Figure 3. SEM images (a) 4 h milled mixture (b) magnified image of 4 h milled mixture (c) compacted and sintered sample of 4 h milled mixture.
Ltd) were used to produce Al-based nano-composites. Figure 1 shows the morphology of flyash (FA), aluminium (Al) and multiwall carbon nanotube (MWCNT) powders. The composite powders were milled by planetary ball milling apparatus at 250 rpm containing stainless steel balls giving a ball-to-powder weight ratio of 8:1. Ball milling were carried out for 1, 2 and 4 h. 3 wt. % methanol were added as a process control agent to avoid agglomeration of powders. 7.6 g of the milled powders were cold compacted in a 12 mm diameter cylindrical die at 285 MPa. Compacted samples were sintered for 1, 3 and 6 h at 500 °C. Argon was used as inert milling atmosphere during sintering.

The tribological properties of hybrid Al based nano-composites were studied using pin-on-disc wear tester (as shown in Figure 2). Cylindrical pins of 12 mm diameter were prepared that slides over 50 mm track diameter of steel disk (counterface). For determining wear loss, the weight of the specimens was measured before and after the wear tests using weight balancing scale with an accuracy of 0.1 mg. Wear rate was determined using the Eq. (1). Wear and wear rate was determined using Eqs. (1) and (2) [8].

Wear (W) = Wf − Wi in grams

Here Wf = Initial weight of specimen in grams. Wi = Final weight of specimen in grams.

Wear rate = \( \frac{\text{Wear loss in grams}(W)}{\text{Sliding distance in meters}(SD)} \) in g/m

Microstructural observations were performed by scanning electron microscope (SEM) in a JEOL-JSM-6380LA.

2.1. Design of experiment

ANOVA and Taguchi analysis of design of experiment were used to provide quick, effective and systematic approach to the optimization of process parameters and to decide their contribution to target parameters. The process parameters considered were sliding speed (SS), sliding distance (SD), load, ball milling time (BM), sintering time (ST), wt. % FA, wt. % MWCNT, and the target parameter was wear loss. The seven process parameters were studied at three levels as shown in Table 1. Table 2 shows the experiments carried out under the L27 design conditions along with wear results. Mean-response graphs were plotted using Minitab-17 software and the percentage of contribution of testing parameters was determined by ANOVA analysis at a level of significance of 5% that is the level of confidence 95%.

3. Results and discussion

3.1. Morphology of the milled mixture and sintered sample

SEM micrograph of the Al/MWCNT - FA powder mixtures ball-milled for 4 h is shown in Figures 3(a) and (b). It can be observed that the reinforcement materials were pierced into the Al powders. Figure 3(c)

| Table 1. Parameters and levels for L27 orthogonal array. |
|-----------------------------------------------------------|
| Levels | FA (wt.%) | MWCNT (wt. %) | Sintering (h) | Ball milling (h) | Load (N) | Sliding speed (rpm) | Sliding distance (m) |
|--------|-----------|---------------|---------------|-----------------|----------|-------------------|---------------------|
| 1      | 4         | 0.25          | 1             | 1               | 10       | 100               | 500                 |
| 2      | 8         | 0.50          | 3             | 2               | 20       | 200               | 1000                |
| 3      | 16        | 0.75          | 6             | 4               | 30       | 300               | 1500                |

| Table 2. Experimental results for Taguchi L27 design. |
|------------------------------------------------------|
| Load (N) | SD (m) | SS (rpm) | FA (wt.%) | MWCNT (wt.% | ST (h) | BM time (h) | Wear (g) | Wear Rate (µg/m) |
|----------|--------|----------|-----------|-------------|--------|-------------|----------|------------------|
| 10       | 500    | 100      | 4         | 0.25        | 1      | 1           | 0.008    | 16               |
| 10       | 500    | 100      | 4         | 0.50        | 3      | 2           | 0.009    | 18.6             |
| 10       | 500    | 100      | 4         | 0.75        | 6      | 4           | 0.013    | 25.2             |
| 10       | 1000   | 200      | 8         | 0.25        | 1      | 1           | 0.014    | 13.7             |
| 10       | 1000   | 200      | 8         | 0.50        | 3      | 2           | 0.018    | 18.3             |
| 10       | 1000   | 200      | 8         | 0.75        | 6      | 4           | 0.019    | 18.7             |
| 10       | 1500   | 300      | 16        | 0.25        | 1      | 1           | 0.035    | 23.33            |
| 10       | 1500   | 300      | 16        | 0.50        | 3      | 2           | 0.035    | 23.27            |
| 10       | 1500   | 300      | 16        | 0.75        | 6      | 4           | 0.042    | 28.13            |
| 20       | 500    | 200      | 16        | 0.25        | 3      | 4           | 0.010    | 19.8             |
| 20       | 500    | 200      | 16        | 0.50        | 6      | 1           | 0.011    | 21.2             |
| 20       | 500    | 200      | 16        | 0.75        | 1      | 2           | 0.015    | 30               |
| 20       | 1000   | 300      | 4         | 0.25        | 3      | 4           | 0.020    | 20.2             |
| 20       | 1000   | 300      | 4         | 0.50        | 6      | 1           | 0.022    | 22.2             |
| 20       | 1000   | 300      | 4         | 0.75        | 1      | 2           | 0.029    | 29.1             |
| 20       | 1500   | 100      | 8         | 0.25        | 3      | 4           | 0.027    | 18.13            |
| 20       | 1500   | 100      | 8         | 0.50        | 6      | 1           | 0.034    | 22.4             |
| 20       | 1500   | 100      | 8         | 0.75        | 1      | 2           | 0.034    | 22.4             |
| 30       | 500    | 300      | 8         | 0.25        | 6      | 2           | 0.008    | 16               |
| 30       | 500    | 300      | 8         | 0.50        | 1      | 4           | 0.010    | 20.8             |
| 30       | 500    | 300      | 8         | 0.75        | 3      | 1           | 0.011    | 22               |
| 30       | 1000   | 100      | 16        | 0.25        | 6      | 2           | 0.024    | 24.3             |
| 30       | 1000   | 100      | 16        | 0.50        | 1      | 4           | 0.026    | 26.1             |
| 30       | 1000   | 100      | 16        | 0.75        | 3      | 1           | 0.034    | 33.9             |
| 30       | 1500   | 200      | 4         | 0.25        | 6      | 2           | 0.030    | 19.93            |
| 30       | 1500   | 200      | 4         | 0.50        | 1      | 4           | 0.037    | 24.73            |
| 30       | 1500   | 200      | 4         | 0.75        | 3      | 1           | 0.045    | 30.33            |
shows the microstructure of the composite sintered at 500 °C for 6 h. It can be seen that grains are refined by cold compaction due to plastic deformation.

### 3.2. ANOVA analysis on wear rate of aluminium hybrid composite

A design parameter is considered important in the Taguchi method if its effect is high compared to the experimental error as calculated by the

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**Table 3. ANOVA results showing the percentage of contribution.**

| Source                      | DF | Adj SS   | Adj MS   | F-Value | P-Value | Percentage of contribution |
|-----------------------------|----|----------|----------|---------|---------|---------------------------|
| Load in N                   | 2  | 61.041   | 30.52    | 7.31    | 0.008   | 10.09                     |
| Sliding Distance in m       | 2  | 31.657   | 15.828   | 3.79    | 0.053   | 5.23                      |
| Sliding Speed               | 2  | 6.684    | 3.342    | 0.8     | 0.471   | 1.10                      |
| FA wt.%                     | 2  | 186.217  | 93.108   | 22.32   | 0       | 30.78                     |
| MWCNT wt.%                  | 2  | 264.403  | 132.202  | 31.69   | 0       | 43.71                     |
| Sintering time in hours     | 2  | 4.079    | 2.039    | 0.49    | 0.625   | 0.67                      |
| Ball Milling time in hours  | 2  | 0.766    | 0.383    | 0.09    | 0.913   | 0.13                      |
| Error                       | 12 | 50.068   | 4.172    |         |         | 8.28                      |
| Total                       | 26 | 604.914  |          |         |         | 100.00                    |

Notes: DF = Degree of freedom, Adj SS = Adjusted sum of squares Sum of squares.
Adj MS = Adjusted mean squares.
F-Value: The F-value is used to determine whether the term is associated with the response. Bigger F-value for a factor represents greater influence of it on response.
P-Value: The P-value for the test measures the probability of obtaining a F Ratio as large as what is observed, given that all parameters except the intercept are zero.
Percentage of contribution (PC) = \[
\frac{\text{Adj SS}}{\sum \text{Adj SS}} \times 100.
\]

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**Table 4. Response table for a mean (smaller the better).**

| Level | Load (N) | SD (m) | SS (rpm) | FA (wt.%) | MWCNT wt.% | ST (h) | BM (h) |
|-------|----------|--------|----------|-----------|------------|--------|--------|
| 1     | 20.58    | 21.07  | 23       | 22.92     | 19.04      | 22.91  | 22.78  |
| 2     | 22.83    | 22.94  | 21.85    | 19.16     | 21.96      | 22.73  | 22.43  |
| 3     | 24.23    | 23.63  | 22.78    | 25.56     | 26.64      | 22.01  | 22.42  |
| Delta | 3.65     | 2.56   | 1.15     | 6.4       | 7.6        | 0.9    | 0.36   |
| Rank  | 3        | 4      | 5        | 2         | 1          | 6      | 7      |

SD = sliding distance, SS = sliding speed, FA-flyash, MWCNT = multi wall carbon nanotube, ST = sintering time, BM = ball milling time.

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Figure 4. Main effect plot for means.
analysis of variance (ANOVA) statistical method. ANOVA is used to analyze the contribution of control factors such as sliding speed, sliding distance, load, ball milling time, sintering time, FA and MWCNT on wear rate. Table 3 represents the percentage of contribution of control parameter on wear rate.

Figure 5. Interaction plot of load, FA and MWCNT.

Figure 6. SEM image of specimen after wear test sliding distance 1500 m, sliding speed 300 rpm and load 30N (a) Al/4%FA-0.25%MWCNT (b) Al/8%FA-0.25%MWCNT (c) Al/16%FA-0.25%MWCNT (d) Al/16% FA-0.75% MWCNT.
The ANOVA table shows the percentage contributions of the testing parameters of MWCNT, FA, load, sliding distance, sliding speed, sintering time and ball milling to be 43.71%, 30.78%, 10.09%, 5.23%, 1.10%, 0.67%, 0.13%, respectively. Thus, MWCNT (wt. %), FA (wt. %) and the load have been found to be the most influential testing parameters on wear rate.

3.3. Taguchi analysis on wear rate of aluminium hybrid composite

The Taguchi technique is devised for process optimization and identification of optimal combination of the factors for a given response. Table 4 shows the response table of Taguchi analysis generated using Minitab -17 software. In general, wear expected to be minimum that is specimen should undergo the least wear. Thus wear quality characteristic selected was smaller is the better type and same type of response was used for signal to noise ratio as given in the following Eq. (3) [24].

\[ n = -10 \log_{10} \text{mean of sum of squares of measured data} \] (3)

Where ‘measured data’ implies the response (wear rate). Higher the signal to noise ratio ‘n’ indicates better the value of control factor which leads to minimum wear rate.

It can be noted that rank is also indicated according to the influence of the control factor on the response. Thus MWCNT wt. %, FA wt. %), load (N) have found to be first, second and third rank respectively indicating most influential control factor on wear rate.

Figure 4 shows the main effect plot for means. It is evident that the lowest peak represents optimized values for the control factor for low wear rate. Thus the optimized values are 10 N, 500 m, 200 rpm, 8 wt. %, 0.25 wt. %, 6 h and 2h for the control factors load, sliding distance, sliding speed, FA, MWCNT, and sintering time, ball milling time respectively. It can be noticed that the main effect plot curve is steeper for FA (wt. %) and MWCNT (wt. %) indicating more influential control factor on wear rate. The influence of interactions between FA (wt. %) - load (N), MWCNT (wt. %) - load (N) and FA (wt. %) - MWCNT (wt. %) is shown in Figure 5. It can be noticed that values for least wear rate are 8 wt. % FA- 10 N load, 0.25 wt. % MWCNT-10 N load, and 8 wt. % FA -0.25wt. % MWCNT.

3.4. Worn out surface analysis

Figure 6 (a-c) depict the type of wear in different worn surfaces of aluminium reinforced with MWCNT and FA composites at load of 30N, sliding distance 1500 m and sliding speed 300 rpm. Ploughing and fragmentation due to abrasive wear mechanism can be seen in Figures 6 (a) and (b). Minor ploughing and fragmentation wear can be noticed in Al/8 wt. % FA- 0.25 wt. % MWCNT composites compared to other composites. This is due to good dispersion and self-lubrication action of the MWCNTs and FA reinforcements in the aluminium reinforced with MWCNT and FA composites. Ploughing occurs due to the generation of groove that does not involve direct removal of material. Fragmentation may be due to the material splits from a surface by a cutting process resulting in a localized rupture. These fractures then grow locally near the wear ploughing, results in spalling. Also adhesive wear mechanism at high content of MWCNTs and FA can be noticed in Figures 6(c) and (d). Adhesive wear occurs due to frictional contact between the surfaces and commonly refers to undesired movement and contact of wear debris and particles from one surface to another [28]. Therefore the present work clarifies that wear in aluminium reinforced with MWCNT and FA composites was due to the combination of abrasive and adhesive wear mechanisms.

4. Conclusions

Following conclusions were drawn from the work.

1. Wear samples of Al/MWCNT-FA nano composites were successfully by PM technique.
2. The results of the microstructure of milled powder and sintered composites showed well dispersion of MWCNT and FA in the aluminium matrix.
3. ANOVA and Taguchi method of design of experiment technique were successfully used to analyse the dry sliding wear of Al/MWCNT -FA nano composites.
4. The ANOVA table shows the percentage contributions of the testing parameters of MWCNT, FA, load, sliding distance, sliding speed, sintering time and ball milling to be 43.71%, 30.78%, 10.09%, 5.23%, 1.10%, 0.67%, and 0.13% respectively.
5. Taguchi results indicated the optimized values for low wear rate to be 8wt. % FA, 0.25wt. % MWCNT, 4 h sintering, 2 h ball milling, 10 N load, 200 rpm sliding speed and 500 m sliding distance.
6. The study of worn surfaces reveal that ploughing and fragmentation wear occur at low content of reinforcements (MWCNT-FA) and ploughing and delamination wear occur at a high content of reinforcements (MWCNT-FA). Minor ploughing and fragmentation wear in Al/0.25 wt. % MWCNT-8 wt. % FA composite attributed to the good dispersion of the MWCNTs and FAs in the matrix.

Declarations

Author contribution statement

Udaya Devadiga: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Peter Fernandes: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] P.K. Rohatgi, A. Douad, B.F. Schultz, T. Puri, Microstructure and mechanical behavior of die casting AZ91D-Fly ash cenosphere composites, Composites Part A 40 (2009) 883-896.
[2] Erik T. Thostenson, Zhifeng Ren, Tzu-Wei Choua, ‘Advances in the science and technology of carbon nanotubes and their composites’ a review, Compos. Sci. Technol. 61 (2001) 1899-1912.
[3] M.K. Surappa, Aluminium matrix composites: challenges and opportunities, Sadhana 28 (February/April 2003) 319–334. Parts 1 & 2.
[4] V. Viswanathanan, T. Laha, K. Balani, A. Agarwal, S. Seal, Challenges and advances in nanocomposite processing techniques, Mater. Sci. Eng. RS 54 (2006) 121–285.
[5] P. Ravindran, K. Manisekar, P. Rathika, P. Narayanasamy, Tribological properties of powder metallurgy – processed aluminium self-lubricating hybrid composites with SiC addition, Mater. Des. 45 (2013) 561–570.
[6] J. David Raja Selvam, B.S. Robinson Smart, J. Dinabhanan, Microstructure and some mechanical properties of fly ash particulate reinforced AA6061 aluminium alloy composites prepared by composting, Mater. Des. 49 (2013) 28–34.
[7] M. Alnouruzzaman, A review on the utilization of fly ash, Prog. Energy Combust. Sci. 36 (2010) 327–363.
[8] M. Ramachandra, K. Radhakrishna, Effect of reinforcement of flyash on sliding wear, slurry erosive wear and corrosive behavior of aluminium matrix composite, Wear 262 (2007) 1450–1462.

[9] E. Marin, M. Lekka, F. Andreatta, L. Fedrizzi, G. Itskos, A. Moutsatsou, N. Koulouzas, N. Kouloumbi, Electrochemical study of Aluminum-Fly Ash composites obtained by powder metallurgy, Mater. Char. 69 (2012) 16–30.

[10] Meftah Hrairi, Mirghani Ahmed, Yassin Nimir, Compaction of fly ash–aluminum alloy composites and evaluation of their mechanical and acoustic properties, Adv. Powder Technol. 20 (2009) 548–553.

[11] P.K. Robatgi, D. Weiss, Gupta Nihal, Applications of fly ash in synthesizing low-cost MMCs for automotive and other applications, J. Miner. Met. Mater. Soc. 58 (2006) 71–76.

[12] Narasimha Murthy, Venkata Rao, Babu Rao, Microstructure and mechanical properties of aluminium-fly ash nano composites made by ultrasonic method, Mater. Des. 35 (2012) 55–65.

[13] R. George, K.T. Kashyap, R. Rahul, S. Yandagni, Strengthening in carbon nanotube/ aluminium (CNT/Al) composites, Scripta Mater. 53 (2005) 1159–1163.

[14] P.J.F. Harris, Carbon nanotube composites, Int. Mater. Rev. 49 (1) (2004).

[15] (a) Bartosz Hekner, Jerzy Myalski, Natalia Vale, Agnieszka Boter-Prohiercz, Malgorzata Sopicka-Lizer, Jakub Wiewior, Friction and wear behavior of Al-SiC(Cn) hybrid composites with carbon addition, Composites Part B 108 (2017) 291e306; (b) Lin Wang, Heekyu Choi, Jia-Min Myoung, Woong Lee, Mechanical alloying of multi-walled carbon nanotubes and aluminium powders for the preparation of carbon/metal composites, Carbon 47 (2009) 3427–3433.

[16] (a) Pankaj Shrivastava, Syed Nasimul Alama, Deepankar Panda, Santosh Kumar Sahoo, Taraknath Maity, Krishnun Biswas, Effect of addition of multiwalled carbon nanotube/graphite nanoplatelets hybrid on the mechanical properties of aluminium, Diam. Relat. Mater. 104 (2020) 107715; (b) C.F. Peng, D.Z. Wang, X.X. Zhang, A.B. Li, Processing and properties of carbon nanotubes reinforced aluminum composites, Mater. Sci. Eng. 444 (2007) 138–145.

[17] R. Pérez-Bustamante, C.D. Gómez-Esparza, I. Estrada-Guel, M. Miki-Yoshida, L. Licea-Jiménez, S.A. Pérez-García, R. Martínez-Sánchez, Microstructural and mechanical characterization of Al-MW/CNT composites produced by mechanical milling, Mater. Sci. Eng. 502 (2009) 159–163.

[18] Qiang Liu, Liming Ke, FenCheng Liu, Chuming Huang, Li Xing, Microstructure and mechanical property of multi-walled carbon nanotubes reinforced aluminum matrix composites fabricated by friction stir processing, Mater. Des. 45 (2013) 343–348.

[19] H.J. Choi, S.M. Lee, D.H. Bae, Wear characteristic of aluminium-based composites containing multi-walled carbon nanotubes, Wear 270 (2010) 12–18.

[20] J.M. Torralba, C.E. da Costa, F. Velasco, P/M aluminium matrix composites: an overview, J. Mater. Process. Technol. 133 (2003) 203–206.

[21] J.S.S. Babu, C.G. Kang, H.H. Kim, Dry sliding wear behaviour of aluminium-based hybrid composites with graphite nano-fibre-alumina fibre, Mater. Des. 32 (2011) 3920–3925.

[22] S. Basavarajappa, G. Chandramohan, Wear studies on metal matrix composites: a Taguchi approach, J. Mater. Sci. Technol. 21 (6) (2005).

[23] S. Suretha, R.K. Sridhara, Effect of the addition of graphite particulates on the wear behaviour in aluminium–silicon carbide–graphite composites, Mater. Des. 31 (2010) 1804–1812.

[24] Siba Sankar Mahapatra, Saurav Datta, A grey-based Taguchi method for wear assessment of red mud filled polyester composites, Int. J. Model. Optimiz. 1 (No. 1) (April 2011).