Dry sliding wear characteristics of multi-walled carbon nanotubes reinforced Al-Si (LM6) alloy nanocomposites produced by powder metallurgy technique

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Keywords: LM6 alloy, wear, nanocomposites, powder metallurgy (PM), multi-walled carbon nano tubes (MWCNTs)

Abstract
The present work involved the production of Metal Matrix Composites (MMCs) of Aluminium Silicon (Al-Si) alloy reinforced with Multi Walled Carbon Nano Tubes (MWCNTs) using Powder Metallurgy (PM) process. MWCNTs with concentrations of 0, 0.25, 0.5, 0.75 and 1.0 wt% were used. Validation of dispersion nature, existence and chemically stable of MWCNTs carried out using Transmission Electron Microscope (TEM), X-ray Diffractometer (XRD) and Energy Dispersive Spectrum (EDS) for fabricated composites. Sliding wear investigations were investigated in accordance with the ASTM G99-95a standard. Test variables such as sliding distance, load and speed were examined. Under a given load with sliding distance, the wear rate was found to reduce by varying disc rotation speed between 250 to 750 rpm. The rate of wear is dropped suddenly with the increment in sliding distance from 500 m to 1000 m. However, for 1500 m sliding distance, the wear rate increased linearly for all nanocomposites. The reinforcement of 0.25 wt% and 0.5 wt% of MWCNTs shown lower wear resistance and further addition of 0.75 wt% MWCNTs shown enhanced wear resistance but the addition of reinforcement of above 0.75 wt% resulted in slightly higher wear rate. The wear resistance enhanced due to the excellent properties of reinforcement particles. The Scanning Electron Microscope (SEM) was used for identifying the kind of wear mechanism.

1. Introduction

In the present market, most of the production engineering sectors choose Aluminium [Al] alloys for light weight applications due to its lower density. These alloys are chemical resistant, better ductile and strengthened material than pure soft silver color Al. The automobile, aircraft and some other engineering segments have shown restraints to use of Al alloys due to its limited strength, rigidity, wear and friction resistance. Recently, Al and Al alloy-based composites, particularly Al nanocomposites were developed to accomplish the need for required mechanical properties, thermal performance, wear resistive, low denser, low energy consumption in manufacturing and ease to make any required component profile [1, 2]. Mechanical ball milling route improved particle refinement in Al-Si alloys. The Si substance enriched the mechanical properties in terms of lengthening the limits of solid solubility. This led to better uniform distribution causing higher strength in alloys. Milling and rolling were also found to dissolve Si elements effectively into Al. Currently, Carbon Nano Tubes (CNTs) are being explored as reinforcements to be added to Al alloys. CNTs have higher specific strength and stiffness properties. The collective techniques of particle refinement, alloying and MWCNTs reinforcement have been reported to offer strength coupled with ductility [3]. The literature reviewed shows that for effective distribution of CNTs in the Al matrix, a high energy mechanical ball milling fabrication technique is used. This method,
however, limits the realization of the full potential that could be offered by the MWCNTs as ball milling method would damage MWCNTs. The CNTs reinforced metal matrix composites to enhance the wear behavior [4].

To get the homogeneous distribution of CNTs reinforcement in the matrix, wetting of CNTs by the matrix is essential [5]. For this, the most effective fabrication route is the Powder Metallurgy (PM) process [6, 7]. PM processed composites have shown improved hardness, strength, and stiffness. Also, resistance to oxidation and wear, minimum coefficient of friction and thermal expansion, with good dimensional stability along with a lower density of the material. Therefore, structural and tribological components in automobile, aerospace and other engineering industries can make use of such nanocomposites [2].

The present study aims to make use of an Al-Si alloy, improve its wear resistance by reinforcing it with MWCNTs material to form a composite. Al-Si alloy with varying concentrations of MWCNTs was produced via PM route and was investigated with respect to their wear characteristics. Characteristics of wear such as disk speed, traversing distance, and applied load were assessed. The worn-out surface was examined under a scanning electron microscopy.

2. Methodology

2.1. Specimen preparation

The procured MWCNTs were purified using concentrated Nitric acid. Following this, they were washed in deionized water to wash off the excess acid content after purification. Finally, the washed MWCNTs powder was by heating it to about 230 °C. Commercially procured Al-Si (LM6) alloy was used as the matrix material. From this alloy, specimens that accurately weighed 35 grams were obtained. To the weighed 35 gm LM6 alloy the required wt% of MWCNTs were added. The blend of alloy-MWCNTs was then mixed in a porcelain container manually. An undue chemical reaction between the constituents of the composite was avoided by using ethanol during the mixing process. The composite precursor thus obtained was ultrasonicated for 30 min. The ultrasonicated aggregate was vacuum dried at 120 °C to eliminate any moisture before the commencement of ball milling.

To break the clusters of composition material, the aggregate was subjected to high energy mechanical ball milling. The composite material was ball milled at 200 rpm for 10 min to obtain a uniformly mixed MWCNTs reinforcement in the LM6 metal matrix.

A metallic die that was intended to be used for fabricating the composite material into test samples was machined in accordance with the ASTM B-925-03 standard. The interior surface of the die was layered with zinc stearate coating facilitate extrusion of the composite through it. The uniformly mixed material was packed into the die and a load rate of 10 kN/minute was given during the extrusion process using a universal testing machine. It was found by trial and error that for LM6 material about 160 kN load would be optimum for compaction in order to achieve enhanced dense material. The compressed composite was sintered in a vacuum furnace under an inert atmosphere at 490 °C. During the heating phase, a heating rate of 10 °C/minute was given followed by soaking of the composite for about 60 min after attainment of the set temperature. The sintered material thus obtained was extruded through the die to obtain a product having a 10 mm diameter. The drawing speed during the extrusion process was maintained at 1.2 mm/second with an applied pressure of 21 MPa [8, 9].

X-ray Diffractometer (XRD) (JEOL -JDX-8P) analysis of the procured LM6 alloy and the fabricated nanocomposites was carried out. Scanning speed of 0.25°/minute was used over a position range of 20–80°.

Figure 1 shows the XRD spectrum of LM6 alloy and the nanocomposites used in this study. The absence of carbide peaks confirms the non-reaction of the matrix material and MWCNTs reinforcements. To validate the presence of MWCNTs in the composite, Energy Dispersion Spectroscopy (EDS) analysis was done using a Scanning Electron Microscope (JEOL 6380 LV). Figures 2(a) and (b) show the EDS image of LM6 and LM6 + 0.5 wt% MWCNTs nanocomposites respectively. The existence of carbon and the composition of LM6 can be clearly seen in these images. The existence of a carbon peak improves the bonding of matrix and reinforcement. Further, it causes delayed pullout of CNTs from the matrix [10].

Figure 3 shows Transmission Electron Microscope (TEM) images of LM6-MWCNTs reinforced nanocomposites with various concentrations. The morphology and the distribution of MWCNTs nanoparticles in the LM6 matrix is clearly observed in the TEM images. The distribution of MWCNTs was seen to be better with 0.5 wt% reinforcement. The 1.0 wt% nanocomposite showed slightly cluttered MWCNTs while considerable clustering was seen with 1.5 wt% MWCNTs. This may have been due to the presence of very fine-sized and homogeneously dispersed Si in the matrix material.
Figure 1. XRD pattern of as received Al-Si (LM6) alloy and those of the fabricated nanocomposites.

Figure 2. Energy Dispersion Spectroscopy image of (a) LM6 (b) LM6 + 0.5 wt% MWCNTs.
2.2. Experimentation
Examination of wear rate was conducted by using Ducom computerized pin on disc wear apparatus as per the ASTM G99–95a standard. The test pieces for wear had a cross-section of 8 mm in diameter and were 30 mm in length. The specimen was placed on a rotating disc with its diameter in contact with the disc. The disc was made with EN 31 steel that was toughened to 60 HRC. It had an outside diameter of 165 mm and a surface roughness of 1.6 Ra. Experiments of wear were conducted at room temperature under ambient conditions. Dry sliding wear investigations were carried out under loads of 10, 15 and 20 N. Wear studies were also conducted at disc speeds of 250, 500 and 750 rpm and at traversing distances of 500, 1000 and 1500 m. After every test for the specific trial parameters, the specimen was taken off from the jaw and debris detached using acetone. The pin weight was recorded before and after the completion of the trial using a digital weighing setup, that had an accuracy of 0.0001 g. The pin wear (micrometer) and developed friction force (N) were measured by the pin on the disc instrument. The rate of wear (mm$^3$ m$^{-1}$) was determined by considering the mean of three trials based on the ratio of volume loss to sliding distance.

3. Results and discussion

3.1. Hardness study
Rockwell hardness measurements were investigated in accordance with ASTM E18-02 standard. For test 1/16th inch diametric indenter of hardened steel was taken for this. For every test piece, five trials were taken at a minimum gap of 5 mm among indentation. Figure 4 shows the mean hardness obtained for each prepared material. Hardness was obtained to increase with the increase in nanoparticle concentration up to 0.5 wt% MWCNTs. This was due to the uniformly spreading of MWCNTs in the matrix of LM6. Hardness increased with the concentration of 0.5 wt% of MWCNTs because of its existence at the interface boundary. However, dislocation of the particles reduced and strain hardening took place during plastic elongation [11]. With further addition in reinforcement concentration, hardness was found to decrease [12, 13]. In the present study, the least hardness was obtained with 1.0 wt% MWCNTs in the LM6 matrix. The jumbled of MWCNTs increased beyond 0.5 wt% reinforcement due to which agglomeration occurred. This lead to the lower the interface bond between MWCNTs and matrix material which in-turn reduced the resistance to the indentation causing easy slide of material.

3.2. Dry sliding wear experiment
Under mutually contact between sliding surfaces, loss of material occurs due to the growth of the minute crack or deformation of the surface followed by removal of such surface from the bulk material. Wear rate of LM6 Al-Si alloy reinforced with varying percentage of MWCNTs were obtained. Rate of wear with varying disc rotation speed, traversing distance and applied load was found. The extent of wear with respect to the variables are plotted in figures 5 to 7 for pure LM6 and MWCNTs reinforced nanocomposites. Figures 5, 6 and 7 indicate the wear behavior for a constant traversing distance of 1000 m, under a constant, applied loads of 10, 15 and 20 N respectively with variation in the sliding speed from 250 to 750 rpm increment of 250 rpm.

These plots show that the resistance to wear is increased with the increase of disc rotation speed. Under a load of 10 N, the wear rate for nanocomposites having a concentration greater than 0.5 wt% showed an increase in compared to matrix LM6 alloy and is shown in figure 5. In figure 6, 0.5 wt% and 0.75 wt% MWCNTs gave a higher and lower rate of wear respectively compared to the base material. The rate of wear decreased with the
concentration of MWCNTs up to 0.75 wt%. However, there was an increase in the wear rate with 1.0 wt% MWCNTs reinforcement as seen from figure 7. Furthermore, it was noticed that the wear rate decreased with the increasing sliding disc speed with increased magnitude load and at a given constant sliding distance [4, 12–17]. The higher hardness material is worn more compared to the lower one. The wear rate increases because of the reduction of the load-carrying capacity of the material [18]. Wear loss reduces with MWCNTs reinforcement. In a cluster of MWCNTs the detachment of MWCNTs taken place gradually not at one point, the existence of detached MWCNTs inbetween counter faces minimized the wear rate even though the hardness is less. Resistance to grain detachment is better in MWCNTs reinforced composite because matrix material grain bounded by MWCNTs [19].

At lower speed, rate of wear is more in compare to higher speed. The loss of material taken by the abrasion wear mechanism at lower disk speed [17]. The decrease in the rate of wear with increased sliding speed was credited, since the development of a solid film. The constituents increased, within the film at higher sliding speeds causing a lubricating effect that led to a reduction in the rate of wear.

Under ambient conditions, the development of a tribolayer was observed with MWCNTs reinforced Al-Si composite (figure 8). The formation of a carbon layer served as a solid lubricant at a higher speed in order to reduce the rate of wear. This finding is in agreement with those obtained in the literature published by Kumar et al [15]. Clustered MWCNTs were pulled out during sliding. These clusters divide independently in the contact zone due to the shearing effect and slide in between contact faces to reduce wear [11]. The growth of carbon film
between counter faces behaves as a solid lubricant, so decrease in COF and wear. The solid self-lubrication layer avoids the contact of pin and disk and due to easy roll or slipping of detached MWCNTs in the contact zone minimizes the worn particle adhesion [6, 12, 19]. The agglomeration percentage is more at 1.0 wt% MWCNTs nanocomposites in compare to 0.75 wt%, which increases the wear rate [20].

The behavior of wear rate for varying traverse distance at sliding speeds of 250, 500 and 750 rpm respectively under a constant load of 20 N is shown in figures 9, 10 and 11. The mixed rate of wear trend was observed with an increase in the sliding distance [17, 18]. Al-Si alloy and 0.5 wt% MWCNTs showed an increasing and decreasing trend within the traversing distances between 500 to 1000 m and 1000 m to 1500 m respectively.

LM6 concentrated with 0.25, 0.75 and 1.0 wt% MWCNTs showed the opposite trend. The wear behavior was enhanced with 1.0 wt% of reinforcement while the 0.75 wt% MWCNTs showed a decreasing wear rate. These findings clearly showed that 0.75 wt% MWCNTs reinforced composite material was exhibited better wear characteristics compared with those of the LM6 alloy and other nanocomposites as shown in figure 9. The figures 10 and 11 shows that the wear rate was reduced between the sliding distances of 500 and 1000 m under a force of 20 N with sliding speeds of 250, 500 and 750 rpm. Further increase in the amount of reinforcement beyond the 0.75 wt% showed deterioration, the extent of wear under the above test conditions.

The addition of MWCNTs up to 0.75 wt%, further addition shown slight higher wear rate in comparison to 0.75 wt% MWCNTs is observed in figures 10 and 11. The wear decreased with the increment of sliding duration is noticed [14]. The hot extrusion process resulted in better densification and a strong bond between the matrix
Figure 8. Development of Tribolayer for LM6 + 0.5 wt% MWCNTs.

Figure 9. Wear rate for varying the sliding distances at 20 N and 250 rpm.

Figure 10. Wear rate for varying the sliding distances at 20 N and 500 rpm.
and reinforcement to minimize the wear rate \[20\]. Resistance to wear reduced even though the hardness increased with the MWCNTs addition due to the reduced bond with the matrix and more agglomeration of the reinforcement \[21\]. MWCNTs resisted the applied load and avoided the matrix material detachment by holding the Al-Si grains. The carbon layer evolution prevented the direct mutual contact of the pin and the disk so that the material loss would be reduced \[17\]. Figure 12 shows the plot of coefficient of friction (COF) at traversing distances of 500, 1000 and 1500 m under a constant applied force of 20 N for the alloys under consideration. It is evidenced by the figure that the COF is a function of the distance traversed for the materials. As sliding progresses between the mating surfaces, the softer metal (LM6 and its nanocomposites) undergoes localized plastic deformation. Further, the temperature at the interface would reach a considerable value causing increased oxidation of the plastically deformed material thereby developing an oxide layer that is brittle. This layer is known as mechanical mixed layer \[15, 22\]. The sliding speed affects the COF at a lower speed, in comparison to higher sliding speeds (irrespective of loads). The COF decreases with the increase of applied load, the lower COF is observed at higher load. There no such variation of COF at lower wt% but it decreases with the higher wt% CNTs addition to the matrix due to the satisfactory solid lubrication availability at the contact area \[18\].

The growth of the carbon solid layer acts as a lubricant to reducing wear. In its early stages of development, this layer is unstable causing increased wear (below the sliding distance of 500 m). As the lubricating layer stabilizes and forms as an interfacial layer between the hard disk of the equipment and the LM6 alloy and its
composites, it causes a reduction in the rate of wear. However, with increased time as the sliding distance was increased (beyond 1000 m), the lubricating film was destabilized which in-turn again resulted in an increased wear rate. When sliding distance increases, there is high material loss from the matrix material and composites [17, 22]. The wear rate is high for less than 0.5 wt% MWCNTs reinforcement Al-Si Alloy and least for 0.75 wt% MWCNTs nanocomposites.

Figure 13 revealed the nature of wear as a function of the load applied at a disc sliding speed of 250 rpm and a sliding distance of 1500 m. The wear rate is clearly seen to increase with increasing load [14, 15, 17, 22, 23]. Wear
rate increased with the increase in normal load due to the increase in plastic deformation and it made direct contact between counterparts [12, 18]. The addition of 0.25 and 0.5 wt% MWCNTs gave elevated wear rate while the wear rate was found to be lower for the 0.75 and 1.0 wt% MWCNTs compared to LM6 alloy. At higher load the LM6 and 0.25 and 0.5 wt% nanocomposites become soft and recrystallization took place because of the generation of high temperature, so wear is high [15]. At higher load, the pullout of reinforcement is more due to the plowing of the matrix material so COF reduces. However general tendency is COF increases with an increase in applied load [12, 18]. At higher load the wear is maximum due to the surface rupture, the delamination wear mechanism was identified [17].

Figure 14(a) shows the micrograph of an LM6 + 0.5 wt% MWCNTs composite surface that is not subjected to higher wear. It shows the morphology of the MWCNTs dispersion in LM6 material. Uniform dispersion gives a smooth surface, whereas rough surface noticed where agglomeration identified due to the weakened area. Voids were created due to non-uniform dispersion of CNTs [11].

The soft abrasive chip, thin flakes at lower load and rough thicker flakes at higher load represent the higher wear. On the worn face, the groves are parallel to the sliding direction and the width and depth of the groves varied with the applied load and sliding speed. Plowing marks are seen on the worn surface and abrasive wear mechanism observed even at the lower load. The presence of a solid lubrication layer avoids the growth of the adhesion of worn particles. Thin, slightest depth and smooth grove were noticed for low load and speed condition and reverse trend for higher speed and load. The formation of oxide taken place with a raise in temperature with an increase in sliding duration [18, 22–29]. The plain and smooth wear tracks can observe in nanocomposites shown in figures 14(b) to (e), the MWCNTs reinforcement minimizes the adhesion and plough wear in comparison to LM6 [4, 13].

The week van der Waals forces among the MWCNTs and matrix caused easily slip or spin in between two contact surfaces and behaved as spacers leading to minimized friction and wear [6, 12]. Soft track on worn surface compared to the base material. Plowing marks were observed on the worn surface at the initial stage later delamination. The amount of debris obtained is less in CNTs reinforced composites [20]. The adhesion and ploughing are caused wear, the delamination is the important wear mechanism in Al-Si material is shown in figure 14(f) [27, 28]. The MWCNTs pulled out on the worn surface is noticed in figure 14(g). A cavity indicates pullout it increases lubrication so decreased in loss of material. The one end of CNTs are at the surface while the other within the matrix, the uncovered CNTs behaves like a solid lubricant between the nanocomposites and counter surface, so the wear is minimum because of friction reduction. The existence of MWCNTs at the boundaries of particle resist the growth of crack and bridges the grain boundaries, it acts as a barricade for the material wear is shown in figure 14(h) [13, 23]. The wettability of MWCNTs and Al-Si alloy matrix is good so it reduces the wear [5]. Exposed MWCNTs indicates the load transferred to CNTs and showing resistance to rupture and bridging the matrix material [30].

The stress developed in the nanocomposites is transferred efficiently via strong interfacial boundary to the MWCNTs, with minimal harm to the reinforcements, it makes composite is stronger. At the interface, composites produced through PM route improves the wetting and other properties of composite and it aids in load transfer by bridging the MWCNTs to the Al-Si alloy matrix. The lubrication behavior of reinforcement reduces the friction and MWCNTs behave as spacers and it enhance the resistance to wear by avoiding the direct contact of the counter disk and matrix [6].

4. Conclusion

The Al-Si—MWCNTs reinforced metal matrix nanocomposites dry sliding wear study showing the followings

- The uniformly distributed MWCNTs in Al-Si alloy showed decreased wear rate with increased sliding disc speed.
- With higher sliding disc speed, the worn surface was observed to be smooth in comparison with the surface obtained at lower low speed.
- The growth of the tribolayer between the Al-Si alloy and the disc caused the wear during longer sliding distance to be almost equal to those obtained under shorter sliding distances.
- An increase in load applied caused increased wear rate, because of the increase in temperature that accompanied the increased load.
- The 0.75 wt% MWCNTs metal matrix nanocomposites showed improved wear resistance in comparison to other concentrations used.
Acknowledgments

One of the author Mr Shivaramu H T would like to express his gratitude to the Department of Material Science, Mangalore University. He is also grateful for the material characterization facility provided by N I T K, Surathkal. He would also like to thank K V G College of Engineering, Sullia, Karnataka for providing experimental facility.

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References

[1] Abdullah U, Maleque M A and Nirmal U 2013 Wear mechanisms of CNT-Al nano-composite Procedia Engineering 68 736–42
[2] Umma A, Maleque M A, Iskandar I Y and Mohammed Y A 2012 Carbon nanotube reinforced aluminium matrix nano-composite: a critical review Aust. J. Basic & Appl. Sci. 6 69–75
[3] Choi H J, Shin H J, Min B H and Bae D H 2010 Deformation behavior of Al–Si alloy based nanocomposites reinforced with carbon nanotubes Elsevier Composites: Part A 41 327–9
[4] Bastwros M M H and Esawi A M K 2013 AbdallawiFi, Friction and Wear behavior of Al–CNT composites Elsevier Wear 307 164–73
[5] Liu Z Y, Xiao B L, Wang W G and Ma Z Y 2012 Singly dispersed carbon nanotube/aluminum composites fabricated by powder metallurgy combined with friction stir processing Elsevier, Carbon 50 1843–52
[6] Bakshi S R, Lahiri D and Agarwal A 2010 Carbon nanotube reinforced metal matrix composites—a review, taylor & francis group Int. Mater. Rev. 55 61–64
[7] Liao J, Tan M J, Ramaanujan R V and Shukla S 2011 Carbon nanotube evolution in aluminum matrix during composite fabrication process Mater. Sci. Forum 690 294–7
[8] Umashankar K S, Alva A, Gangadharan K V and Desai V 2009 Damping behaviour of cast and sintered aluminium ARPN Journal of Engineering and Applied Sciences 4 66–71
[9] Umashankar K S, Gangadharan K V, Desai V and Shivamurthy B 2010 Fabrication and investigation of damping properties of nano particulate composites Journal of Minerals & Materials Characterization & Engineering 9 19–30
[10] Ostovan F, Matori K A, Toozandeliehjani M, Oskouieain A, Yusoff H M, Yunus R and Arifin A H M 2016 Nanomechanical behaviour of multi-walled carbon nanotubes particulate reinforced aluminium nanocomposites prepared by ball milling Materials 9 1 140
[11] Carvalho O, Buciumei inu M, Soares D, Gomes J and Silva F S 2015 Improvement on sliding wear behaviour of Al/cast iron tribo pair by CNT’s reinforcement of an Al alloy Tribology Transactions 58 643–53
[12] Moghadam A D, Omranii E, Menezes P L and Rohatgi P K 2015 Mechanical and tribological properties of self-lubricating metal matrix nanocomposites reinforced by carbon nanotubes (CNTs) and graphene—a review Composites Part B 77 402–420
[13] Shivaramu H T and Umashankar K S 2019 Dry sliding wear behaviour of multi walled carbon nanotubes reinforced aluminium composites produced by powder metallurgy technique Mater. Res. Express 6 115047
[14] Ramesh B T 2014 Characterization of Al based nano composites using powder metallurgy technique International Journal of Research In Aeronautical and Mechanical Engineering 2 131–41
[15] Veeresh Kumar G B, Rao C S P and Selvaraj N 2011 Mechanical and tribological behaviour of particulate reinforced aluminum metal matrix composites—a review Journal of Minerals & Materials Characterization & Engineering 10 59–91
[16] Shivaramu H T, Umashankar K S and Prashantha D A 2018 Wear characteristics comparison of cast and powder metallurgy based Al and Al-Si alloy Mater. Sci. Eng. A 690 818–46
[17] Jeyasimman D, Gurunathan K and Narayanasamy R 2016 Dry sliding wear behaviour of AA 6061-MWCNT nanocomposites prepared by mechanical alloying IOSR Journal of Mechanical and Civil Engineering 13 Ver. IV 46–53
[18] Tabande- Khorshid M, Omranii E, Menezes P L and Rohatgi P K 2016 Tribological performance of self-lubricating aluminium matrix nanocomposites: role of graphene nanoplatelets Engineering Science and Technology 19 463–9
[19] Carvalho O, Buciumeanu M, Miranda G, Costa N, Soares D and Silva F S 2015 Mechanisms governing the tensile, fatigue and wear behaviour of carbon nanotube reinforced aluminum alloy Mech. Adv. Mater. Struct. 23 917–25
[20] Jagannatham M, Senthil Saravanan M S, Sivaprasad K and Kumares Babu S P 2018 Mechanical and tribological behavior of multiwalled carbon nanotubes-reinforced AA7075 composites prepared by powder metallurgy and hot extrusion JIMEPEG 27 5675–88
[21] Bakshi S R, Keshri A K and Agarwal A 2011 A comparison of mechanical and wear properties of plasma sprayed carbon nanotube reinforced aluminum composites at nano and macro scale Mater. Sci. Eng. A 52 83375–84
[22] Manjunatha L H and Dinesh P 2013 Fabrication, microstructure, hardness and wear properties of extruded MWCNT - reinforced with 6061 Al metal matrix composites International Journal of Scientific & Engineering Research 4 974–89
[23] Ahmad L, Kennedy A and Zhu Y Q 2010 Wear resistant properties of multi-walled carbon nanotubes reinforced Al2O3 nanocomposites Elsevier, Wear 269 71–8
[24] Shadakshari R, Dr. Mahesha K and Dr. Niranjan H B 2012 Carbon nanotube reinforced aluminium matrix composites—a review, international journal of innovative research in science Engineering and Technology 1 206–13
[25] Arif S, Alam M T, Aziz T and Ansari A H 2018 Morphological and wear behaviour of new Al-SiC micro-SiC nano hybrid nanocomposites fabricated through powder metallurgy Mater. Res. Express 5 1–26 https://iopscience.iop.org/article/10.1088/2053-1591/aabc0f/meta
[26] Arif S, Tanvir Alam M, Ansari A H, Siddiqui M A and Mohsin M 2017 Study of mechanical and tribological behaviour of Al/SiC/ZrO2 hybrid composites fabricated through powder metallurgy technique Mater. Res. Express 4 075611
[27] Alam M T, Arif S and Ansari A H 2018 Wear behaviour and morphology of stir cast aluminium/Sic nanocomposites Mater. Res. Express 5 1–25 Accepted
[28] Alam M T, Arif S, Ansari A H and Alam M N 2019 Optimization of wear behaviour using taguchi and ANN of fabricated aluminium matrix nanocomposites by two-step stir casting Mater. Res. Express 6 1–19
[29] Shalakany A B E, Kamel B M, Khattab A, Osmanb T A, Azzam B and Zaki M 2018 Improved mechanical and tribological properties of A356 reinforced by MWCNTs Fullerences, Nanotubes and Carbon Nanostructures 26 185–94
[30] Zhou M, Qu X, Ren L, Fan L, Zhang Y, Guo Y, Quan G, Tang Q, Liu B and Sun H 2017 The effects of carbon nanotubes on the mechanical and wear properties of AZ31 alloy Materials 10 1385