Research Summary on the Processing, Mechanical and Tribological Properties of Aluminium Matrix Composites as Effected by Fly Ash Reinforcement

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Abstract: Fly ash is the main waste as a result of combustion in coal fired power plants. It represents about 40% of the wastes of coal combustion products (fly ash, boiler ash, flue gas desulphurization gypsum and bottom ash). Currently, coal waste is not fully utilized and waste disposal remains a serious concern despite tremendous global efforts in reducing fossil fuel dependency and shifting to sustainable energy sources. Owing to that, employment of fly ash as reinforcement particles in metallic matrix composites are gaining momentum as part of recycling effort and also as a means to improve the specifications of the materials that are added to it to form composite materials. Many studies have been done on fly ash to study composite materials wear characteristics including the effects of fly ash content, applied load, and sliding velocity. Here, particular attention is given to studies carried out on the influence FA content on physical, mechanical, and the thermal behavior of Aluminium-FA composites. Considerable changes in these properties are seen by fly ash refinement with limited size and weight fraction. The advantage of fly ash addition results in low density of composites materials, improvement of strength, and hardness. It further reduces the thermal expansion coefficient and improve wear resistance.

Keywords: fly ash; mechanical properties; tribology; metal matrix composites

1. Introduction

In a recent report by the US Energy Information Administration, for the year 2020, coal power plants account for 19.3% of energy source for US, ranked third behind natural gas (40.3%) and nuclear (19.7%) [1]. On a global scale, it represents a bigger share of 36.4% and projected will reduce to 20–25% by 2040 [2] driven by global energy transition policies that promote carbon-free energy sources and reduced dependence on fossil fuels. Coal waste production is recycled and utilized in varying degree for instance, near to 100% in UK, Germany, France and Japan, 80% in China, ranging around 70% in USA, 10% in Russia and Africa whereas for other regions of developing countries, the consumption are lower [3]. Therefore, for the next two decades, coal waste recycling remains as a major relevant concern in many countries.

Waste management covers the aspects of waste reduction, reusing as well as recycling for other practical purposes. Increased global concern on carbon emission prompted the emergence of green policies that dictate the shift towards sustainable energy solutions as well as sustainable waste management approaches. In many less developed nations, coal

waste accumulation required acres of land space and pose serious environmental hazards. Contrariwise, fly ash is considered as valuable secondary raw materials Typical examples are in highway engineering applications such as concrete fillers, road bases, flowable and structural fills, soil modifiers, mineral fillers and stabilizers [4]. Fly ash is an excellent substitute for Portland cement, a main ingredient in concrete. Apart from construction applications, fly ash has also made progress into geopolymers and zeolites production owing to its high silica and aluminium content. Fly ash global market is firmly ingrained in the construction sector, with top fly ash vendors are global market leaders in the production of building materials.

Alternatively, there are also numerous studies available evaluating the potential of fly ash as particulate reinforcement in metal- and polymer-matrix composite. This paper presents summary of recent literatures on the processing of metal matrix composites employing fly ash fillers and in particular for light weight metals such as AMCs and the effects of its addition on the improvement of mechanical and tribological properties. The approaches of reinforcement in metal matrix composite are explained, followed by a discussion on particulate reinforcement in aluminium matrix composites. Thereafter, the main body of this paper highlights relevant researches in the processing, mechanical testing and wear evaluation of fly ash reinforcement in AMCs.

2. Metal Matrix Composites

Reinforcement materials can be categorized as continuous or discontinuous fibers; whiskers [5], particles, and laminated reinforcement [6–8] as shown in Figure 1. Recently, particulate reinforced metal matrix composites have received great attention owing to their economic viability, isotropic properties, and ease of machinability with the same technology used for the unreinforced materials. Moreover, the liquid state processing method i.e., melt stirring process can be easily employed in the preparation of the particulate reinforced Al composites, Melt stir casting has in recent times dominated the manufacturing space because of its relatively low cost and ability to offer a wide range of materials selection and processing conditions [9].
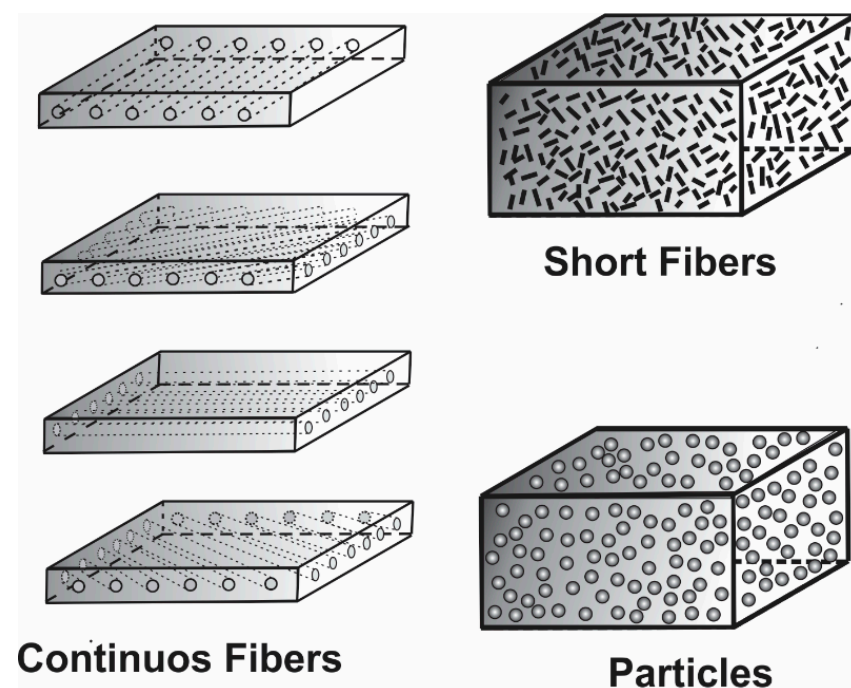

Figure 1. Types of composites reinforcements [10].

The choice of reinforcement is dictated by several factors: primarily, the density and modulus of the reinforcements (low density and high modulus) are important parameters to

be considered for the composites to be used in structural application. More so, the particle geometry may be an essential factor, angular particles can raise local stress and subsequently reduce ductility. Due to their great influece on the strength of composites, the coefficient of thermal expansion and thermal conductivity are important parameters to be considered for the composites to be used in thermal management application [11]. The contributions of different strengthening mechanisms of the composite were evaluated [12]. In general, the selection criteria must be made according to their intrinsc propeties including the chemical composition, melting point, volume shrinkage, density, shape and size, crystal structure, elasticity modulus, diffusivity, hardness, distribution in the matrix among others and finally, availability, ease of prodcution and use. It is noteworthy that oxides from carbides, nitrides, and borides are suitable as reinforcements [13–15].

Meanwhile, several investigations have reported the advantages of employing discontinuous ceramic particulates or whiskers over continuous ceramic fibers for the preparation of aluminum matrix composites AMCs [9,13,16,17]. Nevertheless, the major setbacks encountered in the production of discontinuously reinforced aluminum matrix composites (DRAMCs) are high cost, inferior ductility, low fracture toughness, and low availability of conventional ceramic reinforcing materials especially in developing countries [17–19].

So far, the studies conducted to address these setbacks have largely concentrated on the appropriate selection of suitable reinforcement materials. This indicated of the significance of the reinforcements in estimating the overall performance of the composites. Thus far, the performance of DRAMCs has been improved by three approaches aimed at sourcing for alternative and low cost reinforcements in the development of DRAMCs as well as giving solution to setbacks that posed expensive measures and limited availability of traditional ceramic reinforcement materials [20–23]. Alternative reinforcements that have been studied are industrial and agricultural wastes [21,23,24]. The results from the investigations conducted on the alternative reinforcements showed appreciable improvement in the properties of developed composites relative to the unreinforced alloy. Nonetheless, their properties are inferior to that of DRAMCs fabricated with conventional synthetic reinforcements [25,26].

The second approach involved the optimization of the properties of DRAMCs through particle size reduction (from micro to nano scale) of the synthetic ceramic materials [27–30]. The fracture toughness and ductility of DRAMCs improved without significant drop in strength upon the utilization of nano-particulates as reinforcing materials [27,31–34]. In spite of their marked mechanical property improvement capacity, factors such as high cost and low availability especially for developing countries limits the utilization of nano-particulates. More so, there seems to be an inclusive evidence on the substantial of the mechanisms of ductility and fracture toughness enhancement in nano-particulate reinforced composites. Some investigations have reported strength and wear resistance enhancement at the expenses of ductility [32,33]. The third approach was aimed at developing DRAMCs by using multiple reinforcement materials (hybrid composite). By employing this approach cost reduction and property optimization in DRAMCs can be achieved. Some investigations have reported comparable or improved performance of hybrid AMCs relative to the single reinforced AMCs [35,36].

Metal matrix composites reinforcements have a manifold demand profile, which is determined using production and processing and by the matrix system of the composites material. The following demands are generally applicable [15,37]:

- Low density.
- High service temperature.
- Thermal stability.
- Chemical compatibility.
- High young's modulus.
- Economic efficiency.
- High tensile and compression strength.
- Good processability.

- Minimum ductility.
- Increase fatigue strength.
- Improved wear and abrasive resistance.
- Improve thermal shock resistance.
- Increase in creep resistance at higher temperatures.
- Improved damping capabilities.

These sets of demands are only achievable by utilizing nonmetal inorganic reinforcement materials [15].

3. Particulate Reinforcement

In recent years, particulates reinforced AMCs have shown tremendous potential as structural materials for emerging technologies in aerospace [38], military and transportation industries [39]. The major reason for utilizing particles is to promote the production of low cost composites; hence the reinforcement has to be readily available at an affordable price [11]. Reinforcemnt types play a vital role in the mechanical reliablity of the MMCs. However, they should be nonreactive and stable in the desired operating temperature. Some of the common reinforcements include silicon cirbide(SiC) and aluminum oxide (Al_2O_3), griphite(Gr), cubic boron nitride(CBN), hexagonal boron nitride (HBN), titanium diboride(TiB$_2$), molybdenum disulfide(MoS$_2$), carbon nanotubes(CNT), carbon fibers, FA cenosphers, graphene and numerous nanoparticles. Reinforcements can be in the form of fibers, particles, or flakes [40].

SiC reinforcement enhances the tensile strength, hardness, wear resistance and density of Al and its alloys [41,42] whereas the Al_2O_3 reinforcement exhibited high compressive strength and wear resistance. The boron carbide (B_4C) is among the hardest elements in existence which has high elastic and fracture toughness. However, B_4C inclusion into Al matrix increases the hardness, but doesn't enhance the wear resistance markedly well [43]. As a hybrid reinforcement, zircon enhances the wear resistance remarkable well [44].

In recent years, the utilization of FA reinforcements is due to their low cost and availability as a waste by product in thermal power plants. More so, electromagnetic shielding effect of the Al-MMC was reported to have remarkably improved by utilizing FA reinforcements [40,41,45,46].

4. FA as Reinforcement in Aluminum Composites

FA is produced at 1200–1700 °C from several organic and inorganic constituents of the feed coal during the combustion of pulverized coal in coal fired power stations; as such it is an industrial by product that must be resourcefully utilized so it doesn't become harmful to the environment [47]. Meanwhile, it is on record that the direct utilization of this material in construction projects not only provides solution to the waste management challenges, but it is also an economical alternative to the use of traditional materials. Therefore, the present work is focused on the exploitation of FA waste as a reinforcement phase in the development of the aluminum matrix composite.

The existence of environment regulations industries has promoted the proper management of lightweight ash particles such as FA which is a waste residue from coal burning power plants. A typical Power plant produces 1620 tonnes per day of FA from 18,000 tons of coal burning (9%) [48]. A possible cost effective solution is to utilize FA as composite fillers [49]. Even though, the chemical constituents (SiO_2, Fe_2O_3, CaO, and Al_2O_3) of FA are dependent on several impurities in burnt coal [40]. Mineralogically, the FA constitutes the aluminosilicate glasses containing quartz, magnetite, spinel, hematite, mullite, ferrite, anhydride and alumina [50].

FA particles can be categorized into solid (precipitator), hollow (cenosphere), porous, and irregular particles as shown in Figure 2 [51]. In general terms, the solid spherical particles of FA are known as precipitator FA and the hollow spherical particles with a density below 1 g/cm^3 are known as cenosphere FA. The precipitator FA with a density

range of 2–2.5 g/cm^3 can trigger the enhancement of several properties in selected matrix materials, such as stiffness, strength, wear resistance and density reduction.
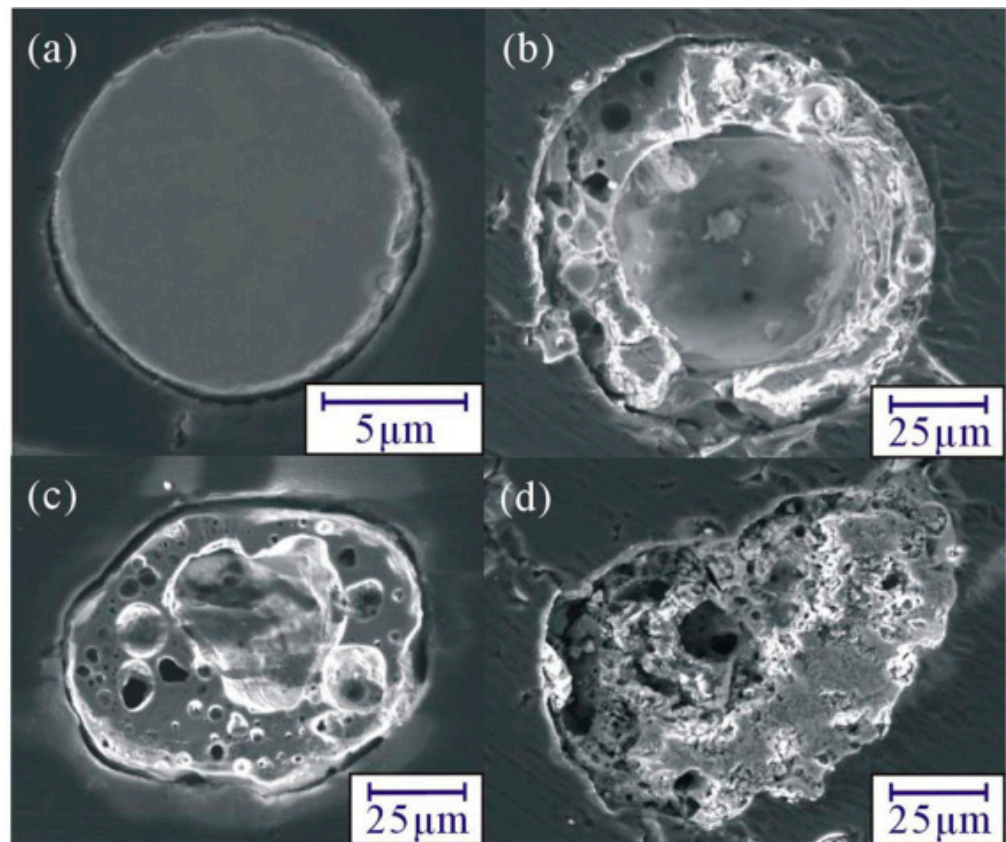
Figure 2. SEM micrographs showing FA structures of (**a**) solid spheres, (**b**) hollow spheres, (**c**) porous spheres and (**d**) irregular particles [51].

Depending on its chemical and mineral constituents, the FA has a tan and or dark grey which can be linked to a high lime content. More so, brownish and dark grey colours can be attributed to the iron content and the elevated unburned carbon content respectively. Figure 3 presents the appearance of FA before and after heat treatment. As presented, it can be evidenced that after heat treatment (preheated in the furnace at 800 °C for 3 h) the colour was changed from dark grey to brownish owing to the removal of unburnt carbon content present in the as-received condition [52]. The thermal expansion coefficient of FA is 6.6 × 10^{-6} °C [53].
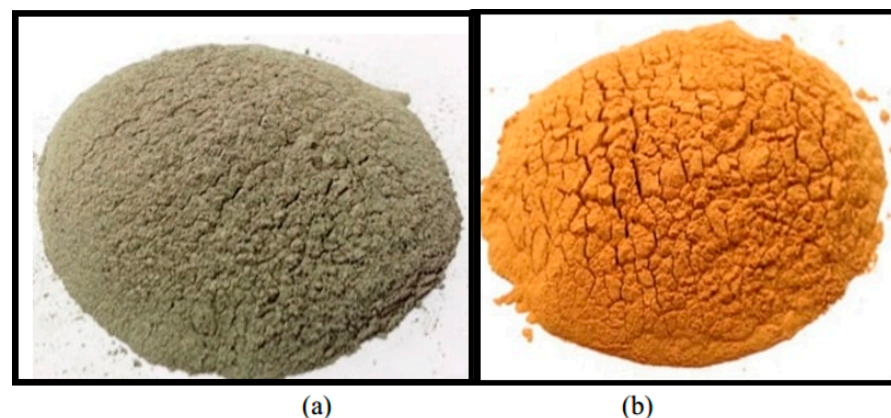
Figure 3. The FA powder used for synthesis of AL-FA composites (**a**) as-received condition, (**b**) after heat treatment condition [52].

Shueiwan et al. [54] fabricated ADC6 that was filled with 5 wt.% FA by stir casting. Preheated fly ash at various temperatures, 400, 500, 600, 660, 700, and 800 °C were added to molten ADC6 at 0.1, 0.15, 0.2 g/s of flow rate. Then, they used the mold Immersed Rapid Solidifications (MIRS) which is a new method to evaluate fly ash composite slurry and create casting specimen for revealing particles distribution in the matrix. Their experimental results revealed the avoidance or minimization of porosity which was made possible by lower addition of FA and higher preheating temperature caused by particle agglomerate in matrix.

The addition of FA particles as reinforcement has lots of benefits for obtaining high structural homogeneity in AMCs [41], and enhances hardness, wear resistance, stiffness, damping properties, and density reduction in Al alloys. Recently, utilization of FA as a reinforcement material in Al alloys has been showcased to be suitable due to its economic viability and resourceful utilization as a waste material [55]. Also, the small particles size (<45 μm) of FA will go a long way in the properties of AMCs [56,57].

5. Fabrication Methods of Aluminum Matrix Composites

Metal matrix composites can be made via liquid, or solid state processes [16,58]. Technically, the development of MMCs using the liquid metallurgy method is more important than the powder metallurgy method [14,15,59]. The method is economical viable and has the capacity of being able to employed in existing casting process for the fabrication of MMCs [60]. Some of the factors to be considered in selecting the processing route include the type and level of reinforcement loading, the matrix alloy, application type, and the degree of microstructure integrity desired [16]. The liquid phase technique involves the introduction of the reinforcement (discontinuous phase) into the metal matrix (continuous phase) which is in liquid state. Through the utilization of conventional casting, the molten metal can be cast into several mold of desired shapes. On the other hand, the solid state process involves the production of particulate-reinforced MMCs through the stepwise blending of the elemental powders followed by consolidation [16]. Several tradtional methods as well as specific patened methods have been utilized in fabrcating AMCs reinforced with varying ceramic particles which include but not limited to powder metallurgy [61], mechanical alloying [62], stir casing [63], squeeze casting [64], compocasting [65] and spray deposition [66]. The mechanical and tribological performance of AMCs are greatly influenced by the processing technique. Improvement of AMCs properties requires an optimal inclusion of ceramic particles into the aluminum matrix. A significant number of processing approaches have been reported on the fabrication of composites by K. Morsi. Approaches discussed include bulk deformation processes such as rolling, 2D forging, equal channel angular pressing, (laser and non-laser-based) additive manufacturing [67]. A Ti-15Mo/TiB metal matrix composite was produced by the spark plasma sintering process [68,69].

Some of the important merits of the melt processing involving the stirring of ceramic particles into melt include, superior matrix bonding, easier control of matrix structure, simplicity, less expensive processing and nearer net shape with wide range of materials for this processing technique [70]. The adhesion between the matrix and the reinforcement phase results in the interfacial bonding. For adhesion to take place in the course of the composites manufacture, the matrix and the reinforcement must be in a close connection with each other. During the developmental stage of composite, the matrix is often in a state wherein it has a high tendency of flowing towards the reinforcement and this behaviour is similar to that of a liquid flow. A key concept in this contact is wettability. Bonding occurs when an intimate contact is established between the matrix and the reinforcement which is due to adequate wetting of the matrix on the reinforcement particles. Many methods have been proposed to overcome the problem of the poor wettability: Preheating the reinforcement particles, Wettability Agents Addition, Fluxes Addition, Coating the Reinforcement Particles, and Compocasting Technique [71].

6. FA Effect on Mechanical Physical Properties of Aluminum Composites Material

Several factors such as type, size, shape, and volume fraction of the reinforcement, matrix material and reaction at the interface affect the mechanical integrity of composites [72]. Hence, it is important to have adequate understanding of the mechanical behaviour of the developed composites so that they can be employed in different areas of applications [73,74]. The complex structure of FA particles makes its usage in FA–reinforced aluminum AMCs very complicated. However, the lowering of density, improvement in elastic modulus, tensile strength and wear resistance of the resulting composites are properties that have increased research interest in the development of FA- reinforced aluminum AMCs.

Rajan et al. [50] evaluated the effect of the manufacturing method on the properties and structure of Al-7si-0.35Mg reinforced with FA particles. They used three different stir casting techniques which are modified compocasting, modified compocasting followed by squeeze casting routes, and liquid metal stir casting. They were well dispersed for fly ash particles distribution by using of modified compocasting cum squeeze, and relatively agglomerate. It enhances the compression strength but it reduces the tensile strength due to particle fracture and particle-matrix debonding. Selvam et al. [75] used composting method to reinforce aluminum alloy AA6061 with volume fraction (0, 4, 8 and 12%) of FA particles for fabrication of composite material. The scanning electronic microscope was used to analyze the aluminum matrix composites AMCs which revealed homogeneous dispersion of the FA with AMCs and there was good bonding associated with clear interface. They reported an improvement in ultimate tensile strength UTS by 132.21% and micorhardness of the AMCs by 56.95% as shown in Figure 4a–c, but the elongation of the AMCs decreased by 63% due to the grain refinement and the ductility reduction of the AMCs.

Dou et al. [76] used two types of FA which are the cenosphere fly ash CFA and the precipitator to reinforce Al2024 alloy and they found that the tensile strength of matrix aluminum reduced by the particles added owing to the inferior mechanical properties of the FA particulate. More so, the fractography studies indicated that AA2024-CFA experienced brittle fracture while AA2024-PFA fractured in a micro ductile manner. Rohatgi et al. [77,78] reported a density decrease in the Al-FA composite after synthesizing cenosphere particles into Al alloy, but observed that pores and cracks in the ash promoted the deterioration of hardness, Young's modulus, and compressive strength.

Anilkumar et al. [23] investigated particle size effect of FA on the mechanical behaviour of AA6061 alloy. Three sets of composites had FA particle size of 4–25, 45–50, and 75–100 μm and reinforcement weight fractions of 10, 15, and 20% were used. Their conclusion revealed that the tensile strength increased with increasing weight content of FA. More so, the tensile strength, compressive strength and hardness of the AA6061 aluminum alloy composites were observed to have decreased with increasing particle size of reinforcement FA. Increasing the weight fractions of the FA particles led to increase in the ultimate tensile strength, compressive strength, hardness, and ductility reduction of the composite. The scanning electron micrographs of the samples indicated uniform distribution of the FA particles in the matrix without any voids. Sudarshan and Surappa [79] prepared A356 Al–FA particle composites by stir cast to reinforce by 6 and 12 vol.% fly ash particles. They observed remarkable increase in micro and macro hardness, as well as excellent mechanical properties with narrow size range of fly ash particles (53–106 μm) performed better than the size range of 0.5 to 400 μm. Suresh et al. [80] reported that by increasing the content of FA, hardness and ultimate tensile strength of LM6-FA composites increased by 34.7% and 44.3% respectively, while the density decreased by 13.2%. The wear loss decreased by 33% at the highest sliding distance.
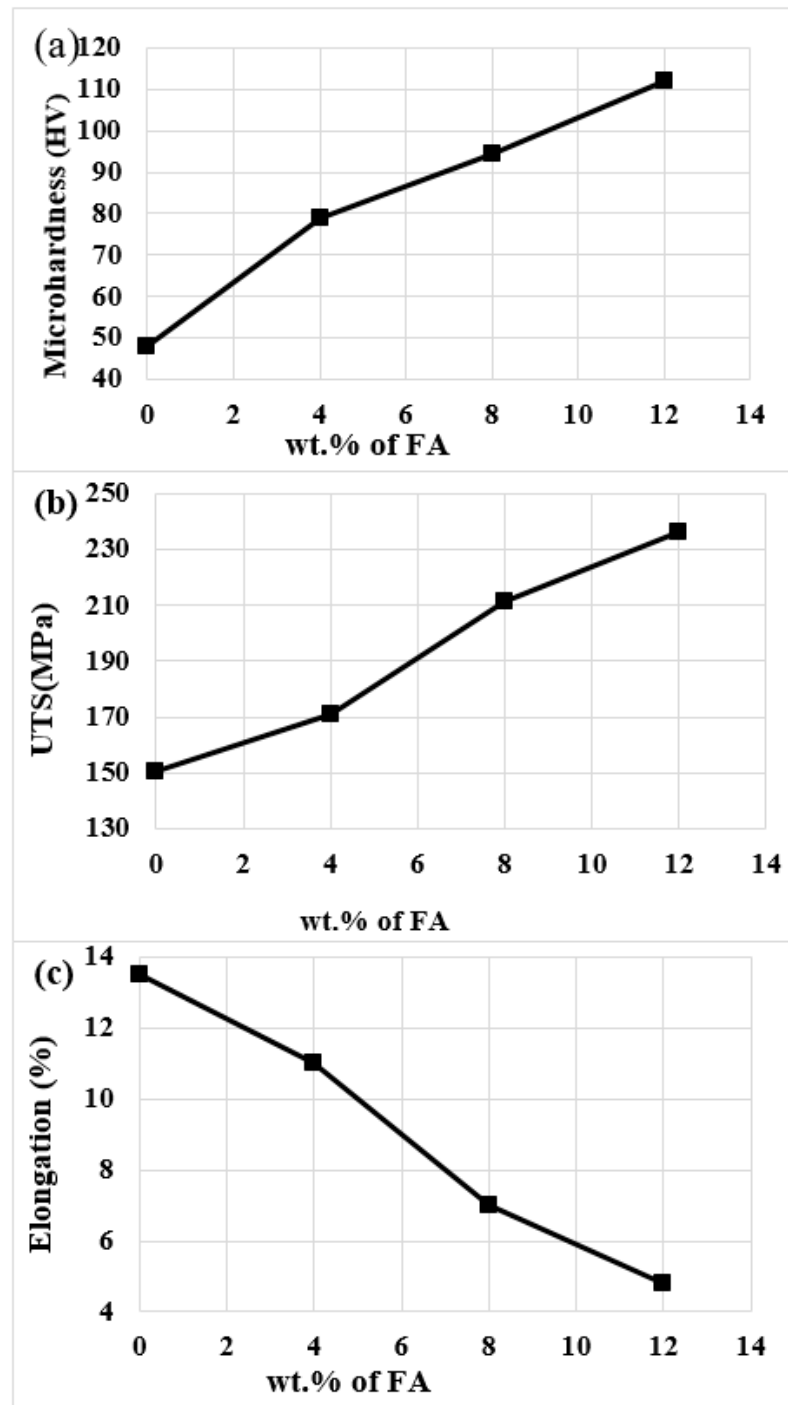
Figure 4. (**a**) Effect of FA content on microhardness (**b**) tensile strength and (**c**) elongation of AA6061-FA compocast composites [75].

Fan et al. [51] fabricated the Al–3Mg/5 wt.% FA composites to study the effect of the period of time for interaction between FA and pure aluminum which contained 3% Mg on the microstructure and mechanical properties. Stir casting method was used to manufacture aluminum composite at 850 °C for different durations (0, 10, 30 and 40 h). They observed reduction of porosity with increasing time, whereas BHN and density increased. They obtained 46.7% improvement of hardness when the duration of reaction was 40 h. θ-Al$_2$O$_3$, MgAl$_2$O$_3$ was obtained by the decomposition of FA particles with prolong time of reactions, Si and Mg formed Mg$_2$Si. The porosity decreased after 30 h reaction due to the decomposition of FA and melt fill by particles. Guo and Rohatgi [81] used pure aluminum

as a matrix to fabricate aluminum-FA composites by powder metallurgy techniques. They observed a slight increase in hardness up to 10 wt.% FA, whereas beyond the 10 wt.% mark, a decrease was reported. Mahendra et al. [82] observed higher hardness for Al–4.5% Cu alloy–fly ash based composites with improvement percentages of 6.7%, 16%, 49%, 128% for hardness, tensile strength, compression strength and impact strength respectively, which increased with an increasing percentage of FA particulates. However, the density decreased with increasing FA content. The maximum density value was 2752 kg/m^3 for base alloy, while the minimum value was 2643 kg/m^3 for composite material at 15 wt.% of FA.

Efzan et al. [57] employed the compocasting method to reinforce LM6 aluminum alloy with different amounts (0, 4 and 6 wt.%) of FA particle. They observed that the inclusion of FA particles enhanced the physical and mechanical properties of the AMCs. Thus leading to the improvement of the energy consumption in automotive parts. The developed AMCs having 6 wt.% of FA reinforcement demonstrated approximately 50 % improvement compared to the unreinforced LM6 alloy. Many researches have used FA as a reinforcement with various grades of aluminum alloy as shown in Table 1.

Table 1. Effect FA on physical and mechanical properties of Al-FA composites.

Author/Year [Ref.]	Process	Filler	Particle Size μm/Fraction%	Main Finding
Rohatgi et al. 2006 [83]	Stir casting and pressure infiltration	AA356 and 319	Fine/3–15 vol.%	• The ability to successfully develop selected prototype castings of Al-FA composites. • The density and coefficient of thermal expansion of casting decreased, whereas their hardness and wear resistance increased with increasing their FA content. • The tensile strength decreased slightly when the FA content was increased.
Dou et al. 2007 [76]	Squeezing casting	AA2024	For CFA is (10–76) μm, for PFA is (10–390) μm/70 vol.%	• The tensile strength of composites decreased with the introduction of FA particulates. • The fractograph studies indicate that AA2024-CFA experienced a brittle fracture while AA2024-PFA fractured in a micro ductile manner.
Rao et al. 2010 [52]	Stir casting	Pure aluminum	60 μm/5–15 wt.%	• FA particles were uniformly distributed in the matrix and also good bonding between matrix and FA. • High amount of FA was required for hardness enhancement of the composite. The increase was observed from 10 HRB for pure aluminum to 45 HRB for 5% and 15% FA composites. • The density of the composites decreased with rising percentages of FA particulates and it came down by 31%. • Minimum compression stress improved by 42%with 50% deformation.
Shanmughasundaram et al. 2011 [84]	Two step stir casting	Al	50–100 μm/5, 10, 15, 20, 25 wt.%	• The density of the composites decreased with increasing FA reinforcement content. • Tensile strength of unreinforced Al increased by 53% after the inclusion of 15 wt.% FA. • The incorporation of FA particles into the Al matrix significantly improved the compressive strength.

Table 1. *Cont.*

Author/Year [Ref.]	Process	Filler	Particle Size μm/Fraction%	Main Finding
Boopathi et al. 2013 [85]	Stir casting	AA2024	0,5,10 wt.% SiC, 0, 5, 10 wt.% fly ash	• SiC and FA particles were properly distributed in aluminum matrix. • The density and elongation of the composites decreased by 20%, and 38.6% respectively. • The yield, tensile strength, and hardness increased by 30%, 24%, and 20% respectively in the presence of 10 wt.% of SiC with 10 wt.% of fly ash.
Arun et al. 2013 [86]	Stir casting	AA6061	1–100 μm /9, 12, 15 wt.%	• The ultimate tensile strength improved by 26.9% with increasing FA weight percentage relative to the base metal. • Compressive strength increased with increasing reinforcement wt.%. • Hardness of aluminum (AA6061) increased from 50BHN to 88HN with inclusion of FA.
Malhotra 2013 [87]	Stir casting	AA6061	5, 10 zirconia wt./10 wt.%	• Tensile strength of 233 MPa was recorded for aluminum alloy 6061 and it rose to a maximum of 278 MPa having an increase in the range of 11–20%. • Hardness value of 78 increased to a maximum of 94 and with range of 6–20%. • Aluminum alloy 6061 exhibited and elongation of 21.66% which was considerably reduced to a minimum of 85% and a maximum of 90% owing to the addition of ceramic material.
Bhandakkar et al. 2014 [18]	Stir casting	AA2024	25–45 μm/5%, 10 wt.%	• Hardness of AA2024-FA metal matrix composites increased with the inclusion of FA particulate reinforcement but the yield strength, tensile strength, elongation, and fracture toughness decreased.
Kulkarni et al. 2014 [88]	Stir casting	AA356 alloy	The average size less than 100 μm/4, 8, 12 wt.%	• Fly ash as areinforcement reduces the density of composite material as well as mechnical properties improved • The compressive strength increased by 16% with 12 wt.% of fly ash. More so, the compressive strength imprvoed by 18% at the presence of 6 wt.% of alumina with 6 wt.% of FA.
Ajit Kumar Senapati et al. 2014 [89]	Stir casting	LM6	5–30 μm/9.8, 10.2 wt.%	• Their results revealed that there is a great effect of reinforcing different FA in aluminum alloy matrix composites. The increase mechanical properties when FA inclusion to base alloy by 200%, 41%,21%, and 18.4% for impact strength, compression strength, tensile strength, and micro hardness respectively.
Senapati et al. 2014 [90]	Stir casting	LM6	63 μm	• The improvement of impact strength, compression strength, and microhardness by 10.2%, 21.09%, and 18.41% respectively.
Arun and Kulkarni 2016 [91]	Stir casting	AA6061	1–150 μm/9, 12, 15 wt.% of fly ash and 6 wt.% of Alumina (Al$_2$O$_3$)	• The ultimate tensile strength has also enhanced with increase in FA weight percentage and compared to base metal it has increased by 21.1%. • The fatigue life has been increased with the increase in weight percentage of FA and it can be seen from S-N curve that Al$_2$O$_3$ 6% give better results when compared to monolithic alloy.

Author/Year [Ref.]	Process	Filler	Particle Size μm/Fraction%	Main Finding
Ilandjezian and Gopalakannan 2017 [92]	Stir casting	AA6061	50–100 μm/1, 2, 3, 5 wt.%	• The ultimate tensile stress value is 12% higher for 5% cenosphere based Al-MMC compared with 0% cenosphere based Al-MMC. The after tensile test area reduction percentage is 8% higher for 5% compared with 0% cenosphere based Al-MMC. The maximum breaking load of 2.45 KN for tensile test occurs at 5% cenosphere and minimum value is 0.14 KN for 0% cenosphere.
Verma et al. 2012, 2013 [93,94]	stir casting technique	AA6063	3, 6, 9 wt.%	• Hardness of Al6063-FA composite increased with increase in Fly Ash percentage but decrease in fatigue strength with increase in FA content. The value of hardness found to be maximum for the 9% fly ash composition at 720 °C at 400 rpm. • It is to be mentioned that even though hardness value found to be maximum for 9% but due to substantial reduction in fatigue strength FA composition of near about 9% at 720 °C with 400 rpm stirring speed is not recommended for fabrication.
Kumar et al. 2014 [95]	Stir casting	AA6063	0.1–100/5, 10 wt.%	• FA up to 10% by weight can be successfully added to AA6063 alloy by stir casting route to produce composites. • FA can be used for the production of composites and turn industrial waste into industrial wealth. This can also solve the problem of storage and disposal of FA. • Strengthening of composite is due to dispersion strengthening and particle reinforcement.

Based on the existing literature review, several research works have focused on the aluminum alloy based composites such as LM6, LM25, A349, AA356, AA357, AA359, AA2024, AA2618, AA2214, AA6061 and AA7075 [76,83,96–99]. However, few investigations have been conducted on the utilization of AA6063 alloy as a base material for the improvement of aluminum matrix composites by FA particles addition [100,101].

7. Effect of FA on Wear Behaviour

Wear resistance of the commercial Al significantly improved with inclusion of FA particles and the wear resistance of the composites was much superior to the aluminum without reinforcement across the board for the load range tested dry sliding conditions [102]. This may be as a result of the favourable effect of the FA particles which was a prevailing factor that affected the wear resistance [103]. However, the inclusion of 20 wt.% FA particle to the Al was very effective in promoting wear loss reduction [84]. Samrat Mohanty and Chugh [104] reported the inclusion of FA particles in automotive brake lining friction composites. The developed brake lining composites demonstrated a reasonable level of consistency in both the wear rates and coefficient of friction. Elsewhere, Al-4.5% Cu-FA composite bush was developed by the stir casting technique [105]. The developed composites bush exhibited more resistance to wear as a compared to the aluminum alloy under lubricated conditions for 200 h. A cylinder liner was cast from the composite and thereafter, it was tested in a two stroke petrol engine. No seizure was detected in the cylinder liner even after 400 h of testing. In their investigation, Selvam et al. [53] observed a rise in the wear rate of FA reinforced AA6061 Al alloy with increasing applied load but decreased with increasing FA content as shown in Figure 5. More so, they observed that the load bearing capacity of AA6061 alloy during dry sliding wear increased in the presence of FA particles. The composites demonstrated superior wear resistance relative to the

unreinforced alloy up to a load of 24.5 N as shown in Figure 6. Generally, the wear rate reduced with increasing particle size of FA particles [56].
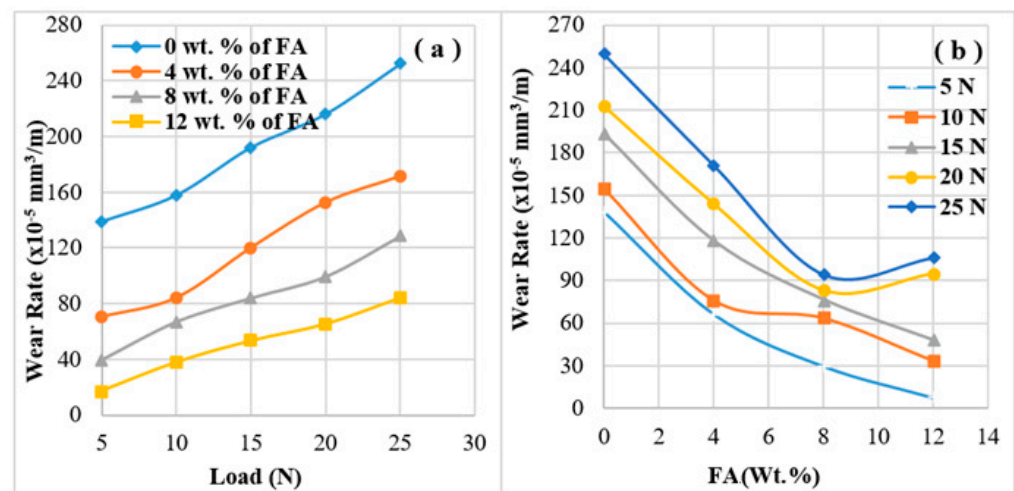

Figure 5. Wear rate of AA 6061 alloy-based MMCs as a function of (**a**) normal load applied; (**b**) wt.% FA [53].
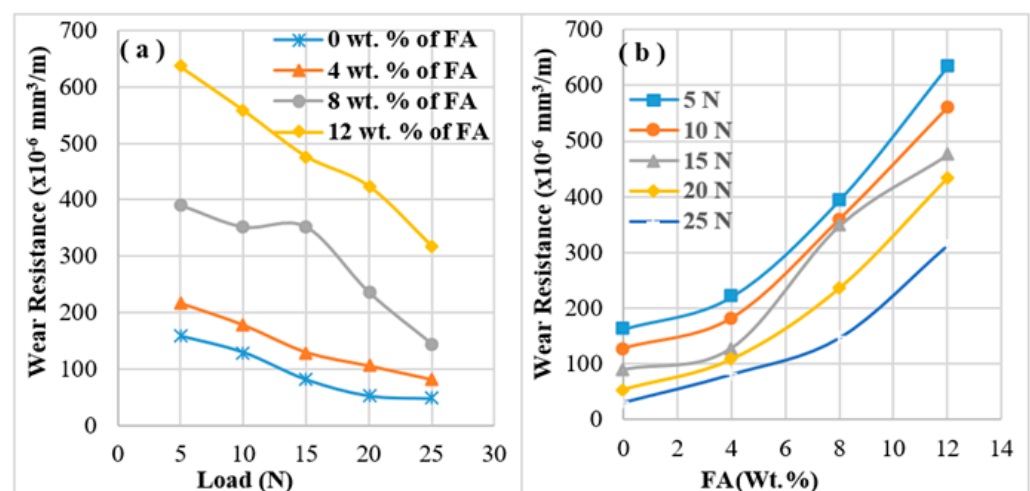

Figure 6. Wear resistance of AA 6061 alloy-based MMCs as a function of (**a**) normal load applied; (**b**) wt.% fly ash [53].

Ravi Kumar et al. [106] investigated the influence of FA particle size and percentages FA content on the wear volume for constant load, speed, and time period. The wear of composites was less than that of the unreinforced aluminum alloy owing to the inclusion of hard FA particles. An increase in the percentage of FA decreased the wear volume at all speeds and loads. This increase can best be explained by the ductility reduction in the composites caused by an increase in hardness owing to the addition of hard FA particles. They discovered that for a given load and speed, rise in FA particle size resulted in the wear volume reduction and vice versa. The possibility for small FA particles to be pulled out from the matrix was greater, hence resulting in an increased wear volume. The matrix held the coarse particles tightly till the particles became fragmented; hence, the wear volume was lower in composites with coarse fly ash particles. In summary, for a given load and speed, the wear volume of the composites decreased with an increasing percentage of FA and particle size.

8. The Coefficient of Friction

Coefficient of friction can be defined as the ratio of the force of friction between two bodies and the force pressing them together [107]. Ravi Kumar et al. [106] studied the

influence of particle size, reinforcement content, load and speed on the coefficient of friction at constant load and speed. They observed that the coefficient of friction decreased with an increase in fly ash content at a constant load and speed. The coefficient of friction of composite materials was greater than that of the aluminum alloy. The coefficient of friction also increased with an increase in FA particle size. The rise in the abrasive resistance by coarse particles most likely explained the increase in coefficient of friction and therefore decreased the wear volume. They observed for a constant FA particle size and percentage of FA, a rise in load and speed decreased the coefficient of friction. Rao and Das [108] investigated the influence of SiC content and sliding speed on wear performance of aluminum composites. They observed that the coefficient of friction increased with increasing of SiC content, but decreased with rising sliding speed. In summary, the coefficient of friction decreased with an increase in the percentage of FA, load, and speed and increased with an increase in particle size. Table 2 show many studies have been conducted to investigate the frictional and wear behaviour.

Table 2. Investigations regarding wear behavior of Al-FA composites.

Author/Year [Ref]	Matrix	Avg. Size (μm)	FA Content	Load N	Velocity	Main Out Finding
Ramachandra and Radhakrishna 2007 [109]	Al(Si 12.2%)	10	0, 5, 10, 15 wt.%	4.9, 9.8 and 14.7 N	500, 600, 700 and 800 rpm	- The purpose of increasing reinforcement on the wear performance of the MMCs was to enhance the wear resistance and coefficient of friction reduction. - The MMC exhibited better wear resistance (20–30% improvement) owing to its superior load bearing capacity. - Increased applied load and sliding speed enhances the magnitude of wear and frictional force.
Suresh et al. 2010 [80]	LM6	150–212	1,3,6,10 wt.%	9.8	500 rpm	- The wear loss declined by 33% at highest sliding distance. - Specimens' analysis revealed there was a direct correspondence between the FA content and the wear loss: the higher FA content, the lower wear loss, and vice versa. Where the wear loss was 0.1 g at 10% FA compared with 0.13 g at 1% FA for a sliding distance run of 7536 m.
Shanmughasundaram et al. 2011 [84]	Pure aluminum	50–100	0,5,10,15,20,25 wt.%	5 and 15	0.5 and 1 m/s	- The work hardening of the aluminum occurred during the sliding action and also the formation of iron oxide film (Fe_3O_4) on the surface of sample which enhanced the wear resistance. - Wear resistance of the commercial Al significantly improved with the addition of FA particles and the wear resistance of the composites became more superior to the unreinforced aluminum across the board for the load range tested under dry sliding conditions.

Table 2. *Cont.*

Author/Year [Ref]	Matrix	Avg. Size (μm)	FA Content	Load N	Velocity	Main Out Finding
Rao 2012 [110]	AA2024	100 to 350 mesh	5 wt.%	−14.7	2 m/s	- The composite demonstrated better wear resistance than the base alloy for the lower loads. - The wear was extensive in Al-FA composites for higher loads and longer sliding distances, owing to the presence of dislodged and fractured FA particles in the alloy matrix.
Natarajan et al. 2012 [111]	AA6061	53–75	3, 6, 9 wt.% FA and fixed 3 wt.% Gr	9.81, 19.62, 29.43	2, 3, 4 m/s	- The load was the most prevalent parameter that influenced the dry sliding wear rate of hybrids composites.
Prasad and Ramachandra 2013 [112,113]	LM6	10–250	5, 7.5, 10, 12.5 wt.%	47,71,95	250, 300, 350 rpm	- It was also discovered that as the squeeze pressure increased the hardness and the wear resistance improved concurrently. - The order of the controllable factors effect on the wear resistance of the composites is wt.% FA content, squeeze pressure, and squeeze time.
Suragimath and Purohit 2013 [96]	LM6	150μm SiC(black), 100μm FA(brown)	5, and 15 wt.% FA, with keeping SiC constant (5%)	4.9, 14.5	300, 500 rpm	- LM6 alloy and SiC FA where selected as matrix and reinforcement materials respectively. The finding showed that in the wear resistance of samples increased with rising inclusion of FA
Uthayakumar et al. 2013 [107]	AA6351	2–10	5, 10, 15 wt.%	9.81, 19.62, and 29.43	1, 2, and 3 m/s	- The experimental results revealed that the composites maintained the wear resistance properties at lower loads with rising FA content. - The applied load and sliding velocity are the most important factors, and it was reported that their contributions to wear performance are 49.71% and 30.43% respectively. - The optimal design parameters were predicted (load = 19.62, sliding velocity =3 m/s, and FA content = 5 wt.%)
Vivekanandan and Arunachalam 2013 [49]	1–100 μm/5, 10, 15, 20 wt.%	Stir casting route.	Pure aluminum			- Both the wear rates and the frictional forces declined remarkably with the addition of FA in the Al melt.
Udaya Prakash 2013 [114]	LM6	75	3, 6, 9 wt.%	15, 30, 45	0.5, 1, 1.5 m/s	- Load ($p = 34.78\%$) had the highest effect on the wear rate accompanied by sliding distance ($p = 22.02\%$), sliding velocity ($p = 15.94\%$) and weight percentage of reinforcement (P9.56). - Sliding velocity ($p = 74.83\%$) had the highest influence on coefficient of friction followed by load ($p = 3.27\%$), weight percentage of reinforcement ($p = 3.18$) and sliding distance ($p = 3.05\%$)

Table 2. *Cont.*

Author/Year [Ref]	Matrix	Avg. Size (μm)	FA Content	Load N	Velocity		Main Out Finding
Kumar et al. 2014 [95]	AA6063	0.1–100	5, 10 wt.%	5, 10, 15	0.5, 1.0, 1.5 m/s	-	Both the wear rates and the frictional force declined remarkably with the addition of FA in aluminum melt.
Viney Kumar et al. 2014 [115]	AA6061	100	10, 15, 20 wt.%	30	1000, 1500, and 2000 rpm	-	Specific wear rate decreased with inclusion of FA up to a specific content. On the other hand, it decreased with graphite inclusion.
						-	Specific wear rate increased with increasing r.p.m. in (20% fly ash and 4% graphite). This was as a result of excess amount of fly ash which made the material so brittle.
						-	Specific wear rate decreases up to 1500 r.p.m. in (10% fly ash and 4% graphite) and (15% fly ash and 4% graphite). This was attributed to the lubricant behaviour of graphite. As the r.p.m. increased, the heat generated by high speed graphite diffused which made the composite more ductile.
Qingping 2014 [116]	Al-25Mg	5–50	5, 10, 15, 20 wt.%	78, 98, 118, 137, 157	400 rpm	-	The coefficient of friction steadily decreased relative to that of the Al alloy matrix at the lower FA content and loads.
						-	The wear mechanism was characterized as abrasive wear and adhesive wear under small applied load at low FA content, and it is characterized as delamination wear and abrasive wear transferred onto the counterpart under high applied load and at high FA content.
Kountouras et al. 2015 [117]	AA7075	65	>40%	5, 10, 15	0.5 m/s	-	The high content of the FA reinforcement (>40%) in the composite material increased wear rate as a result of the FA particles fragmentation.
Selvam et al. 2017 [118]	AA6061	1–2	(0, 4, 8 and 12 wt.%)	24.5	157	-	The tests were carried out at different temperatures of 40, 80, 120, 160, 200 and 240 °C without any lubrication. Applied temperature significantly influenced the mode of wear. The mode of wear was observed to be abrasive at room temperature and adhesive at high temperature.

Many types of aluminum matrix alloy were used to fabricate aluminum composites material for the study of wear behavior, however, it was difficult to establish a general relationship for the wear of composites and sliding velocity. The tribolayers were separated and metal to metal contact initialized. At high sliding speed, large frictional heat emerged and it led to large plastic deformation. These factors promoted the bulk removal of materials from the wear surface and the wear tracks have been observed in some of the investigations. The effect of the parameters (load, sliding velocity) must be simultaneously evaluated in order to determine the wear behaviour of AA6063-FA composites under increasing weight FA contents precisely.

9. Conclusions

There exists a broad data base in the literature for various reinforcements, however that of utilizing FA reinforcement is rarely reported. The addition of FA particles as reinforcement is beneficial in obtaining high structural homogeneity in AMCs, and enhances tensile strength, hardness, stiffness, wear resistance, and reduced thermal expansion, density, and impact energy of Al alloys. Recently, it has been reported the utilization of FA as a reinforcement in Al alloys is desirable from both environmental and economic owing to its availability as low cost waste material. It was found that smaller particle size (less than 45 μm) of FA can easily give superior properties. AA6063 alloy can be considered as preferred matrix for the fabrication of particles reinforced aluminum based composites. So far, few investigations have been carried out on the employment of AA6063 alloy as a base material for the improvement of aluminum matrix composites by FA powder addition. More studies revealed that wear and coefficient friction of composites were influenced by reinforcement content, sliding speed, and applied load. Reinforcement particle size was also a factor that influences the wear and mechanical properties of MMCs. Few investigations are available on the impact of FA reinforcement on the mechanical, the thermal, and the wear behaviour of AA6063-FA composites.

A key benefit of the low temperature of liquid state fabrication of AMCs is that some unwanted reactions can be eliminated from the interface between the matrix and diapered reinforcing phases. Compocasting as semisolid melt process prevents the particles from sinking or floating. The particle movements within the semisolid aluminum alloy after stirring was minimal relative to stir casting owing to the enhanced viscosity of the composite slurry. Limited studies reported reactions by FA addition during the composites fabricated by compocasting processing.

Author Contributions: A.M.R. and D.L.M. conceived and designed the theoretical structure of the paper; A.M.R. and U.M.B. compared and analyzed the data; A.M.R. wrote the paper and reviewed by A.M.R., D.L.M., U.M.B. and H.S.S.A. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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