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Review

Review on properties of hybrid aluminum–ceramics/fly ash composites

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Abstract: The production and characterization of metal matrix composites reinforced with fly ash is a very active research area. This paper presents a review on the properties of hybrid aluminum–SiC/fly ash, hybrid aluminum–B_4C/fly ash, hybrid aluminum–Al_2O_3/fly ash, hybrid aluminum–graphite/fly ash and hybrid aluminum–BN/fly ash composites. The major production route utilized by the various authors was stir casting technique and its variant; powder metallurgy was also utilized by few authors. Improved mechanical properties were observed in the hybrid composites, compared to the composites filled with single reinforcements. It was observed that the properties of the composites were influenced by both the volume fractions of the reinforcements in the matrix and the percentage of replacement of the ceramic reinforcements with fly ash in the hybrid reinforcement mixture. In most of the reports, beyond 40 wt% of replacement of ceramic reinforcements by fly ash, the wear resistance, strength and ductility of the hybrid composites excessively reduced (high brittle tendency), while corrosion tendency increased. Generally, the mechanical properties and wear resistance of the hybrid composites were reported to increase with increase in weight fractions of the reinforcement in the composites until about 15 wt%, beyond which the properties depreciate. At the right ratio of the reinforcements in the hybrid mixture and up to about 15 wt% weight fractions of reinforcements in the composites, the reinforcements were reported to distribute uniformly in the matrix. The major observation was that most of the reports focused on the mechanical properties and wear behavior. Reports are lacking on the thermal and electrical properties of hybrid aluminum–ceramics/fly ash composites. Other areas such as hybrid TiC/fly ash composites are yet to be explored.

Keywords: aluminum; hybrid composites; ceramics reinforcements; fly ash; mechanical properties; characterizations

1. Introduction

Metal matrix composites (MMCs) are attractive to the automotive, aerospace and other industries. Compared to monolithic alloys, MMCs have been reported to exhibit lower density and superior mechanical properties such as improved elastic modulus, higher specific strength, and enhanced wear and creep resistances suitable for structural applications [1,2]. Compared to fibre reinforced MMCs, particulate MMCs are utilized due to their relatively low cost of production and isotropic properties [3]. In particulate MMCs, improved properties are obtained by combining the toughness and ductility of the metallic matrix and the hardness, high strength, wear and thermal resistance of the particulate ceramic reinforcements [4]. Generally, high cost of manufacturing has been the major limitation confronting the MMC industry [3], hence, the utilization of cost effective reinforcing materials such as fly ash for the development of MMCs. Some of the properties that make aluminum MMCs attractive for various engineering applications, especially weight sensitive applications are, specific strength and stiffness, hardness, wear resistance and low coefficient of thermal expansion [5]. Although, aluminum MMCs reinforced with particulate ceramics such as SiC, TiC, WC, oxides and borides show excellent mechanical properties and wear resistance, they are limited by high cost and are heavier than the alloy [6]. Fly ash, an industrial residue obtained from the combustion of coal is cheap compared to crystalline ceramics and therefore reduces the cost of composites when utilized as reinforcements. The production of fly ash from thermal electricity generating plants causes environmental pollution; therefore, efforts towards its utilization in productions will contribute to environmental protection. Reports have shown that particulate fly ash (usually below 100 µm in size) disperses in aluminum matrix and aluminum/fly ash composites are characterized by reduced density, increased hardness, increased compressive strength, higher tensile strength at below 15 wt% filler loading, increased wear resistance at below 20 wt% filler loading and reduced impact strength [7–9]. When utilized alone as reinforcing filler in aluminum composite, the strengthening effect of fly ash is however slightly less than those of ceramics such as silicon carbide and alumina [10,11]. In other to exploit both the properties of hard ceramics and fly ash in composites, several works have been carried out in the areas of hybrid aluminum/fly ash composites. This paper reviews the works carried out in the areas of fabrication and properties of hybrid aluminum–ceramics/fly ash composites.

2. Reviews

2.1. Fly ash

Coal fly ash is an industrial waste obtained as a residue from the combustion of coal in thermal electricity generating plant. Fly ash is usually spherical in shape, either hollow or solid. Chemically, fly ash is mainly composed of different oxides in the order of SiO_2 > Al_2O_3 > Fe_2O_3 > other oxides. These oxides have been used as reinforcements in MMCs. The chemical composition of fly ash changes based on the type of coal burnt and the burning condition [12]. The bulk chemical compositions of coal fly ash by regions have been reported [3], and classifications of fly ash (based on ASTM C 618) is shown in Table 1 [3]. Class F fly ash is obtained by burning bituminous coal while class C is obtained by burning sub-bituminous coal and lignite; class F fly ash is preferred to class C for the production of aluminum MMCs because class F contain less CaO in its chemical composition than class C [13]. The typical amount of SiO_2, Al_2O, Fe_2O_3 and CaO contained in fly ash obtained from bituminous coal were reported to be within the range of 20–60%, 5–35%, 10–40%, 1–12% respectively, and about 0–15% LOI; those of fly ash obtained from sub-bituminous coal were reported to be within 40–60%, 20–30%, 4–10%, 5–30% respectively, and about 0–30% LOI; while those of fly ash obtained from lignite were reported to be within 15–45%, 20–25%, 4–15%, 15–40 respectively, and about 0–5% LOI [13]. Fly ash has low density; bulk density range 540–800 kgm^{-3} and packed density within the range of 1120–1500 kgm^{-3} [14], compared to other ceramic reinforcements as shown in Table 2 [15]. Also, the cost of fly ash is low; thus, reinforcing aluminum with fly ash reduces the density and cost of the composite material.

Table 1. Classification of coal fly ash by ASTM C 618 [3].

Class: ASTM C618	$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	Moisture (%)	SO_3 (%)	LOI (%)
C	>50	<3	<5	<6
F	>70	-	-	<12

Table 2. Densities of various ceramic reinforcements [15].

Ceramic reinforcement	Density (×1000 kgm^{-3})
B_4C	2.52
SiC	3.21
Al_2O_3	3.98
TiC	4.93
TiB_2	4.5
SiO_2	2.66

2.2. Hybrid aluminum–SiC/fly ash composites

Amongst the aluminum fly hybrid composites, most reports are on hybrid aluminum–SiC/fly ash composites.

2.2.1. Density, mechanical properties and wear behavior of hybrid aluminum–Sic/fly ash composites

Kanth et al. [16] studied the microstructure, density, hardness, yield and ultimate tensile strengths of Al–Zn alloy based composite filled with SiC/fly ash (ratio 1:1 weight of mixture) at 5 and 10 wt% filler loading and fabricated by stir casting. The major findings from the report of Kanth et al. [16] were uniform dispersion of the hybrid filler in the matrix, no voids, discontinuity and porosity observed in the fabricated composites, 10% and 13% reduction in the measured density of the composites relative to the alloy at 5 and 10 wt% filler loadings respectively, 17.65% and 37.22% increment of hardness with respect to the alloy at 5 and 10wt% filler loadings respectively; and increase in both the yield strength and ultimate tensile strength with increase in filler loading from 5 to 10 wt% relative to the alloy. The major research gaps in the work of Kanth et al. are lack of reports on the properties and microstructure of the composites based on the gradual replacement of SiC by fly ash as their reports were based only on ratio 1:1 weight of mixture of SiC and fly ash. Also, Kanth et al. did not compare the properties obtained in the hybrid composites with the properties obtained when the alloy was filled with SiC only. In a similar work, Mahendra and Radhakrishna [17] investigated the properties of Al–4.5%Cu–(fly ash–SiC) hybrid composites (ratio 1:1 weight of mixture of reinforcements) at 5, 10 and 15 wt% filler loading produced by stir casting. The major findings of Mahendra and Radhakrishna were, uniform dispersion of the reinforcements in the matrix, reduction in fluidity of the melt with increase in filler loading due to obstruction by particles and increase in viscosity, reduced density, reduced wear rate (both abrasive and erosive) and frictional force with increase in filler loading; increase in hardness, tensile strength, compression strength and impact strength with increase in filler loading. Generally, the wear rate increased as the applied load increased. Boopathi at al. [18] further reported that hybrid aluminum alloy 2024 filled with SiC/fly ash (ratio 1:1 weight of mixture) at 10 wt% filler loading offered superior wear resistance compared to the composites filled with only fly ash and only SiC. Also, the tensile strength, yield strength and micro hardness (HV) of hybrid aluminum alloy 2024 filled with SiC/fly ash (ratio 1:1 weight of mixture) at 9 wt% were reported to improve by 16.95%, 19.01% and 10.39% respectively over those of the base alloy; while the parameters for the fly ash reinforced composite were improved by 11.44%, 14.55% and 4.88% respectively, and those of the SiC reinforced composite were improved by 12.29%, 16.82%, 9.14% respectively [11]. It was observed that the percentage elongation reduced with the addition of the fillers, with the hybrid filler having more significant reduction in the percentage elongation when compared to the specimens filled with only SiC or fly ash [11]. At 13 wt% filler loading, the tensile strength, yield strength and hardness of hybrid aluminum alloy 2024 filled with SiC/fly ash (ratio 1:2 and 2:1 weight of mixture) were improved over those of the base alloy by 17.80%, 22.27% and 12.27% respectively (for ratio 1:2 weight of filler mixture); and 20.76%, 25% and 17.52% respectively (for ratio 2:1 weight of filler mixture) [11]. The optimal filler loading for aluminum LM6 alloy filled with SiC/fly ash (ratio 1:1 weight of mixture) produced by stir casting was reported to be 12 wt% [19]. At 12 wt% filler loading, hybrid aluminum LM6 alloy filled with SiC/fly ash (ratio 1:1 weight of mixture) showed 66.69% improvement of the tensile strength, no change in percentage elongation, 17.86% improvement in absorbed impact energy, and 52.05% improvement in wear resistance [19]; these properties are superior when compared to the properties shown by hybrid aluminum LM6 filled with SiC/red mud, which were reported as 54.04% improvement of the tensile strength, 11.33% reduction in percentage elongation, 5.36% reduction in absorbed impact energy, and 29.22 reduction in wear resistance [19]. The report of the effect of gradual replacement of SiC by fly ash on the mechanical and thermal expansion hybrid A356/SiC/fly-ash composites produced by electromagnetic stir casting at 20 wt% filler loading was presented by Dwivedi et al. [13]. A sample each was produced with only SiC and only fly ash respectively; while three hybrid samples were produced by replacing SiC with 25, 50, 75 wt% fly ash respectively in the hybrid A356/SiC/fly-ash composites [13]. The reports of the mechanical properties on both the as-cast and heat treated samples presented by Dwivedi et al. show that that hybrid A356/SiC/fly-ash composite at 25 wt% replacement of SiC with fly ash offered the best improvement in tensile strength, specific strength, impact strength, hardness and fatigue strength compared to the alloy and the sample reinforced with only SiC. The sample reinforced with only fly ash at 20 wt% filler loading offered the least improvement in properties due to agglomeration of fly ash and high porosity. The SiC reinforced sample perfumed better than the hybrid A356/SiC/fly-ash composite at 50 and 75 wt% replacement of SiC with fly ash [13]. All the hybrid composites offered higher specific properties than the sample reinforced with SiC due to lower density of the hybrid composites compared to the composite reinforced with SiC only. Hybrid A356/SiC/fly-ash composite at 20 wt% filler loading with 25 wt% replacement of SiC with fly ash offered the best thermal stability compared with the other samples [13]. Reinforcing aluminum with only fly ash at 20 wt% filler loading resulted to agglomeration of the particles and high porosity which gave rise to poor mechanical properties [13]. Generally, the properties performance of the heat treated hybrid A356/SiC/fly-ash composites were better those of the as cast samples.

By keeping the volume fraction of fly ash constant and gradually increasing the weight fraction of SiC, the wear rate of hybrid aluminum LM24/SiC/fly ash composites was reported to reduce as SiC content increased [20]. The improvement in the machinability, mechanical and tribological properties of hybrid aluminum–SiC/fly ash composites due to addition of fly ash was reported to be due to high surface area of fly ash [21], solid lubricating property of fly ash [22–24] and the prevention of the reactions of carbide and aluminum to form aluminum carbide (Al_4C_3) due to the addition of calcined fly ash [21,22]. Also, the uniform dispersion of the hybrid reinforcements ensures effective transfer of load from the matrix to the reinforcements, thus, enhancement in the mechanical properties. Thus, hybrid aluminum–SiC/fly ash composites offer better mechanical and tribological properties than aluminum/SiC composites only at optimal replacement of SiC with fly ash. The basic rule is for the hybrid composite to contain more SiC than fly ash.

Based on these reports, it can be said that hybrid aluminum–SiC/fly ash composites possess superior mechanical properties and wear resistance over the composites filled with only SiC or fly ash. However, care must be taken in the design of the filler mixture, as both the volume fraction of reinforcements and their ratios in the hybrid mixtures control the properties of the composites. It was reported that the optimal replacement of SiC with fly ash in the hybrid reinforcement mixture should be between 33–40% [23] to achieve synergy between the SiC and fly ash and improve wettability due to the lubricating nature of fly ash. Beyond 40% replacement of SiC with fly ash, the ductility of the composite will be drastically reduced and this may induce brittle fracture. It has been observed that the mechanical properties and wear resistance of the hybrid aluminum–SiC/fly ash composites increases as the volume fraction of the reinforcement increases up to about 15–20 wt% filler loading, beyond which the properties start to depreciate [11,13,22,25–28]. Apart from volume fraction of reinforcements, the wearing conditions such as sliding speed, applied load and sliding distance also affect the wear rate of the hybrid composites. At a particular filler loading, Shaikh [28] established through Taguchi approach and analysis of variance that sliding speed contributed about 74.07%, while applied load and sliding distance contributed about 11.11% and 7.4% receptively to the wear rate. Though powder metallurgy has been used for the fabrication of the composites [25,28], the majority of the hybrid aluminum–SiC/fly ash composites fabricated were produced through stir casting (liquid metallurgy) processing and its variants. The composites were characterized by homogenous dispersion of SiC and fly ash in the matrix. Reports are lacking on the thermal properties and electrical conductivities hybrid aluminum–SiC/fly ash composites.

2.2.2. Corrosion behavior of hybrid aluminum–SiC/fly ash composites

A work carried out by Santhosh et al. [29] on hybrid aluminum 5058 composites filled with SiC/fly ash at 8–14 wt% filler loadings, reveals that the corrosion rates of the hybrid composites in both 1 M HCl and 1 M NaOH solutions decreased gradually as the exposure time increased from 24 to 120 h at 24 h interval. It was however observed that the corrosion rates of the composites were higher in the 1 M NaOH solution compared to the rates in the 1 M HCl solution at all times. Similarly, it was earlier reported also that erosive wear of hybrid aluminum SiC/fly ash composite was more in basic erosive media compared to acidic erosive media [17]. Santhosh et al. [29] however observed that as the percentage of fly ash in the hybrid SiC/fly ash filler increased, the corrosion rate also was found to increase; and this is similar to the report on the corrosion of Al–4.5Cu–(fly ash–SiC) composites earlier reported [17] showing higher corrosion rates with increase in the addition of fly ash. It may therefore be undesirable to design hybrid aluminum–SiC/fly ash hybrid composites containing more fly ash than SiC in the hybrid filler mixture for applications in corrosive environments. In 3.5% NaCl solution, it was also reported that the corrosion rate of hybrid aluminum/SiC/fly composites were higher than aluminuim/SiC composites [18].

Reports are lacking on the electrical properties of hybrid aluminum–SiC/fly ash composites.

2.3. Hybrid aluminum–B_4C/fly ash composites

Researchers have also shown interests on the fabrication of hybrid aluminum–boron carbide–fly ash composites.

Arunachalam and Chelladurai [30] developed wear resistant AA336 aluminum alloy filled with hybrid B_4C/fly ash (ratio 2:1 weight of mixture) at 15 wt% filler loading produced by stir casting. The major findings reported by Arunachalam and Chelladurai [30], were uniform distribution of the hybrid filler in the microstructure. In another report, Canute and Majumder [31] evaluated the mechanical properties of A356 alloy filled with hybrid B_4C/fly ash (ratio 1:1 weight of mixture) at 8 wt% filler loading and produced by stir casting. The major findings of Canute and Majumder [31], were uniform distribution of the reinforcements in the microstucture, increase in the hardness, tensile strenth and compression strength of the Al/B_4C/fly ash composite by 28.19%, 21.9% and 10% respectively as compared with the cast aluminum alloy. Chelladurai et al. [32] also reported the uniform distribution of B_4C/fly ash hybrid filler in LM13 aluminum alloy, and increase in hardness, tensile strength and wear resistance of the composite, with a decrease in percentage elongation as compared with the alloy. In another report, Sahu and Sahu [33] corroborated the uniform distribution of B_4C/fly ash hybrid filler in the matrix of Al 7075 alloy and increase in hardness of the hybrid composite compared with the alloy. Reddy et al. [34] evaluated the mechanical properties and wear rate of hybrid aluminum-7075/B_4C/fly ash composites at 10 wt% filler loading and compared the properties with the unreinforced alloy and the alloys filled with a single reinforcement from 1 to 10 wt% at 1 wt% increment. The reinforcement mixture of B_4C:fly ash in the work of Reddy et al. were 1:9, 2:8, 3:7 and 4:6 respectively. Among the composites with single reinforcements, the best combination of properties were achieve at aluminum-7075/3wt%B_4C and aluminum-7075/7wt%fly ash [34]. The hybrid aluminum-7075/B_4C/fly ash exhibited the best combination of properties at aluminum-7075/3wt%B_4C/7wt%fly ash. The comparison of the best properties of the hybrid composites and the composites filled with single reinforcements is shown in Table 3 [34]. It can be seen from Table 3 [34] that the properties of the hybrid composites were superior to those filled with a single reinforcement. The tensile strengths, impact strengths and hardness of the composites increased with increase in filler loading until the optimal composition, thereafter, it declined. The wear rates are higher at higher applied loads and reduced with filler loading for each applied load up to the optimal composition for each category before it started to increase; while the percentage elongation continued to decrease with increase in filler loading. The microstructure showed that hybrid B_4C/fly ash reinforcements distributes uniformly in the matrix. The improved properties of the hybrid aluminum-7075/B_4C/fly ash over those of the composites reinforced with single filler are due to good interfacial bonding between the two reinforcements.

Table 3. Properties of the aluminum-7075/3wt%B_4C/7wt%fly ash composites and the composites filled with single reinforcements at the composition with the best combination of properties [34].

Property		Percentage (%) increment/reduction of property over the unreinforced alloy at compositions with the best performance among A7075/B_4C/fly ash, A7075/B_4C and A7075/fly ash composites (%)		
		A7075/3wt%B_4C/7wt%fly ash	A7075/3wt%B_4C	A7075/7wt%fly ash
Desired property increment	Hardness (BHN)	36.6	34.1	12.2
	Tensile strength (MPa)	19.5	9.6	1.6
	Impact strength (J)	295	275	205
Desired property reduction	Wear rate (mm^3/m)10^{-3} at different applied loads	Lowest	Lower	Low
Undesired property reduction	Percentage elongation (%)	Reduced from 4 to 0.73	Reduced from 4 to 0.7	Reduced from 4 to 1.5

So far, researchers have commenced works on aluminum–B_4C/fly ash hybrid composites. The reports so far are focused on the mechanical and wear behavior of the hybrid composites. Reports are lacking on the corrosion behavior, thermal properties and electrical conductivities of the aluminum–B_4C/fly ash hybrid composites.

2.4. Hybrid aluminum–Al_2O_3/fly ash composites

The densities and compression strengths of hybrid Al356–Al_2O_3/fly ash composites fabricated by stir casting have been investigated, and it was reported that the hybrid composites (filled with 1:1 mixture of the fillers) presented lower densities than Al_2O_3 reinforced composites from 4–12 wt% filler loading [10]. The percentage porosities of the hybrid composites increased with increase in filler loading, but were within acceptable range at 4–8 wt% filler loading [6,10]. The hybrid aluminum–Al_2O_3/fly ash composites were characterized by reduced compressive strengths when compared with the composites filled with only alumina at 8–12 wt% filler loading due to high porosity; but the compressive strength of the hybrid composite was however higher than that of the sample filled with only alumina at 4 wt% filler loading [10]. At all the compositions, the compressive strengths of the hybrid composites were higher than those of the alloy [10]. Generally, the compressive strength increased with increase in filler loading. In another report, Babu et al. [35] compared the densities, hardness, tensile strengths, and porosities of hybrid aluminum–Al_2O_3/fly ash composites and hybrid aluminum–SiC/fly ash composites (filled with 1:1 mixture of the fillers) at 3, 6 and 9 wt% filler loadings as presented in Table 4. As shown in Table 4 [35], hybrid aluminum–SiC/fly ash composites offered lower density than hybrid aluminum–Al_2O_3/fly ash composites at all filler loadings. Also, the tensile strengths and hardness properties of hybrid aluminum–SiC/fly ash composites were superior to those of hybrid aluminum–Al_2O_3/fly ash composites [35]. It can be seen that from 9 wt% filler loading, the porosity of aluminum–Al_2O_3/fly ash composites exceeds the acceptable range [6]. The optimal percentage replacement of Al_2O_3 by fly ash in the filler mixture was not reported as the above reports were based on 1:1 weight combination of the two reinforcements in the hybrid mixture. There is also the need to further expand the information on hybrid aluminum–Al_2O_3/fly ash composites based wear, microstructural, corrosion, thermal and electrical characterizations.

Table 4. Comparing the mechanical properties and porosity levels of hybrid aluminum–SiC/fly ash and aluminum–Al_2O_3/fly *ash* composites [35].

Hybrid aluminum MMCs	Measured density, ρmd (g/cm^3)	Tensile strength, σts (MPa)	Hardness, BHN	Porosity, ε	Theoretical density, ρtd (g/cm^3)
7075/3% (1.5% SiC + 1.5% FA)	2.78	230.78	190.31	0.451	2.792
7075/6% (3% SiC + 3% FA)	2.76	241.81	231.75	0.54	2.775
7075/9% (4.5% SiC + 4.5% FA)	2.74	253.05	274.31	0.616	2.757
7075/3% (1.5% Al_2O_3 + 1.5% FA)	2.791	222.18	165.56	0.357	2.801
7075/6% (3% Al_2O_3 + 3% FA)	2.78	224.34	181.53	0.429	2.792
7075/9% (4.5% Al_2O_3 + 4.5% FA)	2.76	226.46	207.29	0.862	2.784

2.5. Hybrid aluminum–graphite/fly ash composites

The self-lubricating nature of graphite and light weight of fly ash make the production of hybrid aluminum–graphite/fly ash composites attractive for light weight and self-lubricating applications. Natarajan et al. [36] studied the hardness and wear rate of hybrid aluminum–graphite/fly ash (at 1:1, 1:2, 1:3 ratio of graphite to fly ash reinforcement mixture) at 6, 9 and 12 wt% filler loadings. Reports show that the hardness of the hybrid composites increased while the wear rate decreased with increase in fly ash content in the reinforcement mixture and with increase in filler loading [36,37]. The wear rate decreased with increase in the applied load for all the composite samples and load was reported to be the most significant parameter affecting the wear rate using Taguchi approach [36,37]. Decrease in densities, improvements in the hardness and tensile strengths of hybrid aluminum–graphite/fly ash (at 1:1, 1:2, 1:3 ratio of graphite to fly ash reinforcement mixture) at 6, 9 and 12 wt% filler loadings with increase in fly ash content and filler loading was also reported by

Prasat and Subramanian [36]. Uniform filler distributions of the reinforcements in the composite materials were also observed in the hybrid composites [37]. The tensile strength and hardness of the composite reinforced with only graphite however decreased [37]. The improved mechanical properties of the hybrid composites can be attributed to higher hardness of fly ash compared to graphite.

2.6. Hybrid aluminum–BN/fly ash composites

BN having similar crystal structure with graphite is usually described as white graphite. It is a self-lubricating material. Self lubricating hybrid aluminum–BN/fly ash composites were developed for tribological applications following stir casting process [38,39]. In both reports, the weight fraction of the BN was kept constant at 4 wt% [38] and 5 wt% [39], while the fly ash weight fraction was varied as 5, 10, 15 wt% [38] and 3, 6, 9 wt% [39] respectively. Though, the properties of the hybrid composites were not compared with those of the unfilled alloy and with those filled with only a single reinforcement; it was generally observed that the hardness of the hybrid composites increased as the weight fraction of the fly ash increased while the density and wear rate decreased accordingly. At higher load, hybrid aluminum–BN/fly ash composites were observed to exhibit lower wear rate due to the lubricating nature of BN that lowers the coefficient of friction and the hard nature of fly ash [38,39].

3. Conclusions

The essence of this review is to highlight the progress made in the development and characterizations of hybrid aluminum–ceramic/fly ash composites for diverse engineering applications and to present the research gaps for further research. This review highlighted that the most popular technique that has been used to fabricate hybrid aluminum/fly ash composites is stir casting and its variants, although powder metallurgical processing can be employed. The major findings in the developed hybrid aluminum–ceramics/fly ash composites as reported were homogenous distribution of the hybrid ceramic/fly ash mixtures in the matrix of aluminum alloys, improved mechanical properties, wear resistance and specific properties of the hybrid composites compared to the composites reinforced with single reinforcements. It was established that the optimal replacement of particulate ceramics with fly ash in the hybrid composites should be less than 40% (usually between 30–40%) and the filler loading should not be above 15 wt% to obtain improved mechanical properties and wear resistance over the composites filled with single reinforcement. Above these filler level, the mechanical properties of the hybrid composites deteriorated due to fillers agglomeration and higher porosities; and the corrosion rates became undesirable. Reports showed that the mechanical properties of hybrid aluminum–SiC/fly ash composites are superior to those of hybrid Al_2O_3/fly ash composites. There is room for further research in hybrid aluminum–ceramics/fly ash composites. Generally, reports are lacking on the thermal and electrical properties of hybrid aluminum–ceramics/fly ash composites. Also, TiC and other carbides utilized as reinforcements in aluminum alloys can also be explored in hybrid aluminum–ceramics/fly ash composites in order to develop composites with reduced weight and desirable mechanical properties. In-depth studies could focus on the studies of corrosion rates of hybrid aluminum–B_4C/fly ash composites. The properties of the aluminum–ceramics/fly ash composites prepared using different fabrication techniques can also be studied and reported. Researchers can also evaluate the effects of addition of surface modified fly-ash and surface modified ceramics in hybrid aluminum–ceramics/fly ash composites on their properties.

Conflict of interests

All authors declare no conflicts of interest in this paper.

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