crystals

Review

Trends in Aluminium Matrix Composite Development

Chika Oliver Ujah [1,2,*] and Daramy Vandi Von Kallon [1]

1 Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, P.O. Box 524, Johannesburg 2006, South Africa
2 Africa Centre of Excellence for Sustainable Power and Energy Development (ACE-SPED), University of Nigeria, Nsukka 410001, Nigeria
* Correspondence: omega.ujah@gmail.com

Abstract: Research shows that monolithic Al alloy has very attractive properties required in the production of aerospace, automotive, electrical and electronic, sports and recreational components/equipment. However, its low strength and low wear resistance have challenged its applications in some other critical industrial utilities. Nonetheless, the invention of metal composites has removed such barriers. The addition of one or more reinforcements to Al has helped in the creation of aluminium matrix composites (AMCs), which has not only increased the global utilization of Al alloy, but has been a major source of global revenue and job. This review was, therefore, aimed at studying recent works on AMCs with the aim of ascertaining the recent innovations in the development of advanced Al composites, which can replace steel components in most industrial applications at a cheaper rate. It was observed from the study that AMCs can be developed via solid and liquid fabrication techniques. Powder metallurgy was reported as the most effective method of producing hybrid Al nanocomposites, with spark plasma sintering as the best technique. In the liquid process, stir casting was reported as the most cost effective, but was challenged by agglomeration. It was recommended that agglomeration be ameliorated by cryogenic ball milling and an in situ fabrication technique. It was also recommended that more cost effective agro-waste nanoparticles should be developed to replace more costly conventional reinforcements. In summary, it was recommended that more research on the exploration of Al alloy at a cheaper rate should be carried out.

Keywords: aluminium matrix composites; stir casting; powder metallurgy; spark plasma sintering; aluminium hybrid composites; aluminium binary composites

check for updates

Citation: Ujah, C.O.; Kallon, D.V.V. Trends in Aluminium Matrix Composite Development. *Crystals* **2022**, *12*, 1357. https://doi.org/10.3390/cryst12101357

Academic Editors: Weiwei Zhou and Huakang Bian

Received: 4 September 2022
Accepted: 22 September 2022
Published: 25 September 2022

1. Introduction

Composite materials are obtained by conjoining two or more materials that possess quite dissimilar properties together. Composites consist of a matrix, which is the base material, and one or more reinforcements, which are the dispersed phase. The dissimilar materials (matrix and reinforcement(s)) work in synergy to provide the composite with exceptional characteristics, which neither of them can provide in isolation. The development and use of composites started around 1500 B.C., when early Egyptian and Mesopotamian dwellers used a combination of mud and straw to construct resilient and robust buildings [1]. Straw was the reinforcement for the primordial composites like pottery and boats. Thereafter, in 1200 AD, the Mongols developed the first composite bow [2]. They used a blend of wood, bone, and animal glue. These bows were potent and precise. It was this composite bow that helped Genghis Khan's military to take the centre stage of victory in the ancient wars in the primeval era. Meanwhile, the evolution of the modern composites industry actually started in 1970s when plastic resins and reinforcing fibres were developed. DuPont invented an aramid fibre known as Kevlar, which has turned out to be the choice product for body armour because of its high tensile strength and light weight [3]. Then, there came the development of carbon fibre at almost the same time, where most of the parts made of steel were replaced with it. Carbon fibre has a light weight, high toughness and high strength. The composite industry is still developing, with much interest in nanomaterials that possess extreme small molecular structures and high mechanical characteristics [4]. There are about five different types of composite industries in existence today, namely: ceramic matrix composites (CMCs), carbon–carbon composites (CCCs), hybrid composites (HCs) polymer matrix composites (PMCs) and metal matrix composites (MMCs) [5]. CMCs consist of ceramic as the matrix and fibres, whiskers or particulates as the dispersed phase. They are characteristically resistant to oxidation and degradation at higher temperatures. This composite is ideal for high temperature and strength-demanding applications such as in automobile and aircraft gas turbine engines. However, its susceptibility to brittle fracture restricts its applications. CCCs consist of carbon as the matrix and carbon as the reinforcement. HCs are comparatively new fibre-reinforced composites developed by using two or more different types of fibres in a single matrix. This type of composite has a better combination of properties than composites with a single fibre [6]. PMCs consist of a polymer resin as the matrix, with fibres as the reinforcement. The resin provides the net shape of the composites and transfers the load to the reinforcement, which absorbs the load and gives the composite its requisite strength. MMCs consist of a matrix of a ductile metal and a dispersed phase of particulates, whisker, nanomaterials or fibres. MMCs perform better at elevated temperatures than their base metal counterparts [7]. Light weight metals such as aluminium, magnesium, and titanium alloys are the ideal base matrices used in producing MMCs, and are reinforced with carbides, nitrides, borides, and oxides prepared in the form of particles, whiskers, or fibres [8]. Through the blending and consolidation of the metal matrix and dispersed phase, the composite is enhanced in specific stiffness, strength, wear resistance, creep resistance, thermal conductivity, and configuration stability. Other advantages of MMCs over PMCs include higher temperatures of operation, non-flammability, and higher resistance to degradation by organic fluids [5]. The global demand for MMCs has increased drastically from over 5.5 million kg in 2012 to over 8.8 million kg of MMCs in 2020 [9]. The growth in the development of MMCs has continued to generate enormous wealth for the producing countries, as can be seen in Figure 1.

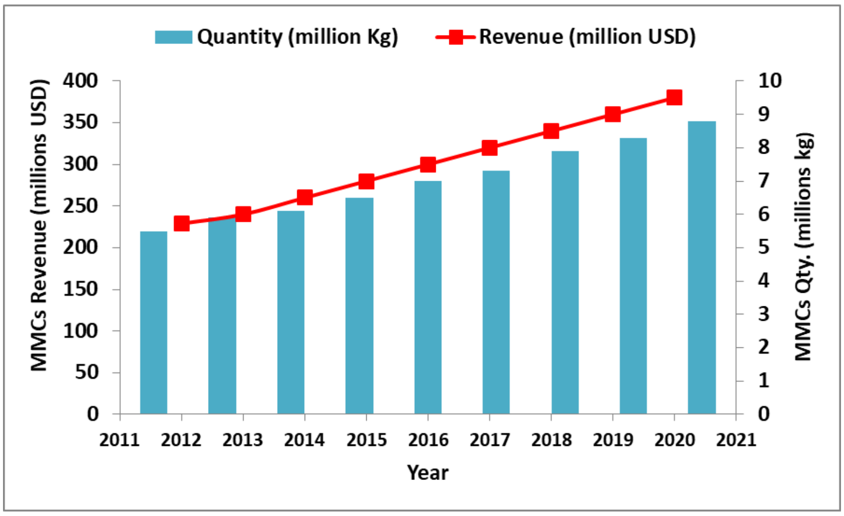

Figure 1. MMCs demand and revenue generated worldwide [9].

Aluminium alloys are the most widely used matrix in the production of MMCs, both in research and development and in industrial applications, because of their low density, cheapness (when compared with other light metals like Mg and Ti), high ductility and high corrosion resistance [10,11]. This alloy is usually reinforced with dispersed phases in order to improve its strength, thermal stability, oxidation resistance, wear resistance, creep resistance and toughness. The choice of reinforcement is based on the application of the composites. Aluminium matrix composites (AMCs) have found wide applications in automotive [12–14], electrical [15–17], aerospace [18,19], marine [20–22], defence/military [23–25], domestic [26–28], medical/surgical instruments [29,30], etc. This is because of their improved physical, mechanical, tribological, thermal and corrosion properties. AMCs possess superior strength, better creep resistance, higher wear resistance, higher corrosion resistance, a lower coefficient of thermal expansion (CTE), a higher modulus and better fatigue strength than monolithic Al alloys [31,32]. A summary of characteristic properties of AMCs necessary for various components developed with the composite is shown in Table 1.

Table 1. Components/products developed from AMCs.

Industry	Products	Properties	Ref
Automotive	Piston and connecting rod, brake and chassis, engine block	Light weight, high thermal conductivity, high strength, wear resistance	[33,34]
Defence	Fins of a directed gun	Precision and strong rigidity	[35]
Sports	Golf, baseball, skiing equipment	Low cost and light weight	[36]
Building construction	Roofing sheet, door and window panels, shelves,	Strength and light weight	[37]
Electrical and electronic	Conductor, capacitor, inductor	Low CTE, high thermal conductivity	[38]
Aerospace	Wings, rudders, flaps, fuselage, fan outlet guide vanes, hydraulic pipes	Good specific stiffness, light-weight and low CTE	[39,40]
Rail and marine	Rail car body, marine ship body parts	Lightweight, high corrosion resistance, high fire hazard control	[41]

In the last decade, many researchers have worked on MMCs, especially AMCs. Authors who have worked on a review of AMCs include [9,42–44]. However, no review has reported the current advancement in AMCs development since 2020, notwithstanding much improvement recorded in this all-important composite. Therefore, this review was aimed at reviewing the latest advancement in the design and production of AMCs with the intention of projecting the advanced techniques, uses, properties, prospects and recommendations for enhancing the production and usage of the composite.

2. Types of Aluminium Matrix Composites

Fibres, whiskers, particulates and nanomaterials of ceramics, non-metals, and polymers are used in the reinforcement of Al light metal. Choice of reinforcements is dependent on the properties being sorted for, which is equally dependent on the end product application. In this section, binary composites, hybrid composites, and Al reinforced with nano-sized reinforcements are discussed.

2.1. Aluminium Binary Composites

In order to improve the mechanical, thermal, tribological and physical properties of the Al matrix, a choice can be made of one type of reinforcement, ceramics for instance, to produce a binary composite system. Ceramics are always the choice material because they possess high hardness, high thermal stability and high wear resistance deficient in monolithic Al. Hence, reinforcing Al with ceramics produces a composite with good ductility, high strength, high formability, high thermal and wear resistance, and high toughness [45,46]. Advanced ceramics such as alumina (Al_2O_3), aluminium nitride (AlN), zirconia (ZrO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), boron nitride (BN), boron carbide (B_4C), carbon nanotubes (CNTs), tungsten carbide (WC), and titanium carbide (TiC) are used to engineer Al into specific configurations suitable for specific applications. Some of the Al binary composites are discussed below:

(i) Al-Al_2O_3 Composite: Alumina or aluminium oxide is one of the most popular fine ceramic materials that possess high chemical and physical stability. It has high thermal resistance and high thermal conductivity; high strength and hardness; high electrical insulation and high corrosion resistance as well as high biocompatibility [47]. These properties make it a suitable material for developing spark plugs, tap washers, abrasion resistant tiles, and cutting tools [48]. The properties of Al/Al_2O_3 composite prepared through powder metallurgy are majorly dependent on the particle size of the powders, as opined by researchers. Finer powders generate higher hardness than coarser particles [49] due to the Hall Petch effect. The porosity of the Al/Al_2O_3 composite, more so, is a function of the particle size of the constituent elements. Finer particle size generates lower porosity than coarse particle size. Incidentally, porosity varies inversely with elastic modulus as reported by Gudlur et al. [50]. It should be noted that the elastic modulus defines the stiffness of composites. Likewise, particle size of the constituent elements varies inversely with the strength, toughness and stiffness of the emerging composite. More so, it was observed that increasing the volume fraction of alumina in Al matrix reduces the coefficient of thermal expansion (CTE); and increases the elastic and shear moduli [50]. Rahimian et al. [51] studied the effect of alumina addition on the properties of an Al alloy matrix. It was observed that by increasing the weight fraction of alumina from 0% to 10% and to 20%, the hardness of the composite increased from 33 to 62 and to 75 BHN, respectively, at a sintering temperature of 550 °C (Figure 2); the compressive strength increased from 133 MPa (pure Al) to 273 MPa (Al-10Al_2O_3), and decreased to 190 MPa (Al-20Al_2O_3); the yield strength increased from 118 MPa (pure Al) to 190 MPa (Al-10Al_2O_3), and decreased to 160 MPa (Al-20Al_2O_3); while the wear rate decreased from 0.0447 mm^3/m to 0.0262 mm^3/m. Therefore, reinforcing Al with alumina not only improved the mechanical properties, but also the tribological properties. However, when the weight fraction exceeded 10 wt.%, most of the properties decreased, except hardness. Hence, 10 wt.% was regarded as the optimum weight fraction of the reinforcement. In another study, increasing the volume fraction of Al_2O_3 to 20% in Al matrix increased the hardness of the composite from 396 MPa to 1355 MPa in a consolidation via spark plasma sintering [52].

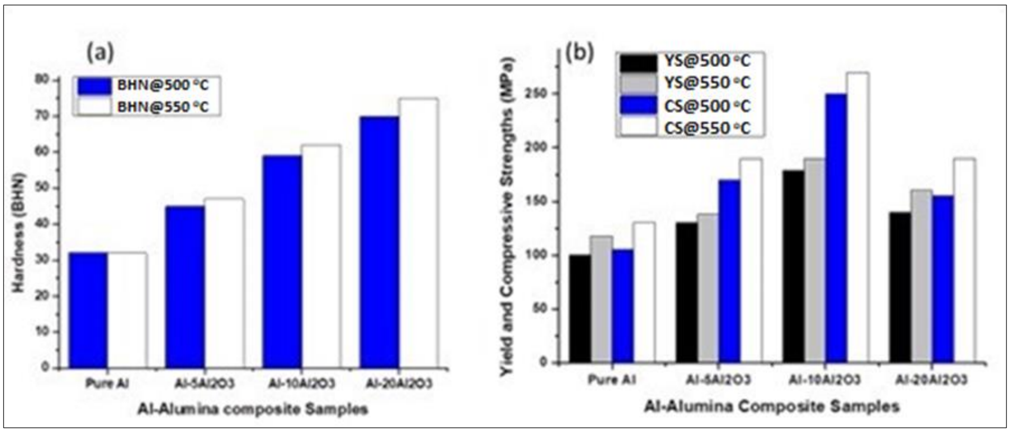

Figure 2. Profiles of (**a**) hardness, (**b**) yield and compressive strengths of Al-alumina composite samples adapted from [49].

Furthermore, good wettability of Al_2O_3 in an Al matrix is another phenomenon that enhances the properties of Al/Al_2O_3 composites. In a study to investigate the effect of wettability, Nourouzi et al. [53] observed that improving the wettability of alumina through milling improved the yield strength of Al/Al_2O_3 by 215% besides enhancing the hardness, wear resistance and the microstructure of the composite. Park et al. [54] studied the effect of Al_2O_3 addition in an Al matrix using volume fractions of 5–30%. It was observed that an increase in the volume fraction of Al_2O_3 reduced the fracture toughness of the

AMC. This was attributed to the decrease in inter-particle spacing between nucleated micro voids. Kok [55] consolidated an Al2024/Al_2O_3 composite with a vortex method in order to study its mechanical properties. The optimum parameters of the technique included a pouring temperature of 700 °C, preheated mould temperature of 550 °C, stirring speed of 900 rev/min, particle addition rate of 5 g/min, stirring time of 5 min and pressure of 6 MPa. The results showed that the wettability and bonding between the Al matrix and Al_2O_3 reinforcement increased with the applied pressure; while the porosity decreased. Therefore, increasing the pressure increased the wettability and interfacial bonding and reduced the porosity. Kumar et al. [56] studied the properties of an Al359/Al_2O_3 composite using an electromagnetic stir casting technique. It was observed that the hardness and tensile strength increased; and it was concluded that the electromagnetic stirring method induced the improvement by producing a composite with a refined grain size and high interface bonding between the matrix and reinforcement. Therefore, the Al/Al_2O_3 composite has proven to be a choice material for industrial, household and high strength applications.

(ii) Al-AlN Composite: AlN is a choice ceramic material for reinforcing an Al matrix in some applications because of its excellent thermal, mechanical and physical properties. It has a high thermal conductivity of over 170W/mK, which is five times greater than that of Al_2O_3 [57]. Its CTE is 4.5 $\times$ 10^{-6} °C, which is almost the same with that of Si (3.5–4 $\times$ 10^{-6} °C). It has good dielectric constant, dielectric loss, bulk resistivity and dielectric strength [58]. Its mechanical properties are excellent, as it has higher bending strength than Al_2O_3 and BeO. Abdoli et al. [59] investigated the effect of AlN reinforcement on the Al matrix via milling in a planetary ball-mill using various percentage weight fractions of 0, 2.5, 5, and 10. The powders were milled for 25 h, degassed, die-pressed uniaxially in steel die and sintered at 650 °C. It was observed that 5 and 10 wt.% of AlN improved the wear resistance of the composite more through increasing its strength against oxidative and abrasive wear in all the applied loads. However, the reinforcement had an insignificant effect on the corrosion current density of the composite in both 0.05 and 0.5 mol/L NaCl medium, but reduced the pitting potential (E_{pit}) in the diluted solution. There was an increase in the thermal conductivity of Al-AlN up to 180 W/mK when a 40–60 volume fraction of AlN was incorporated into the Al matrix, with a great reduction of CTE [60]. The thermal and mechanical properties of the Al-AlN composite were studied by Yu et al. [61]. It was fabricated by in situ hot extrusion at 450 °C with an extrusion ratio of 11:1. Both an AlN-free and AlN-containing lamellar structure along the extrusion direction were produced. Nanoscale AlN particles were well dispersed in the AlN-containing lamellar with excellent interfacial bonding and an absence of voids, stimulated by the in situ method. It was observed that Al/8.9 vol.% AlN had an ultimate tensile strength of 332 MPa and tensile elongation of 3%. However, when the volume fraction was raised to 17.5 vol.% AlN, it had higher tensile strengths of 538 MPa, but there was no tensile elongation to failure. The CTE decreased when the volume fraction of AlN increased, as shown in Figure 3. However, the increase in the temperature increased the CTE as expected. The CTE was low from ambient up to 450 °C, which makes the composite fit for high temperature applications like aerospace nozzles and turbines.

It has been reported that AlN reinforcement can be dispersed unto the Al matrix via ex situ or in situ. In situ provides better dispersion than ex situ, but its commercial scalability (mass production) is still farfetched. However, in order to obtain homogenous dispersion of AlN in the Al matrix, Pradhan et al. [62] employed the in situ method. Hence, an Al-AlN composite was processed by treating molten aluminium with a mixture of CaO and NH4Cl, held at a temperature range of 750–930 °C and then cast into a metal mould. The results showed that a maximum hardness of 572.12 MPa was achieved in the Al-AlN (30–30) composite. When the quantity of NH4Cl + CaO was increased, the wear resistance of the composite increased too. In comparison with other heat resistant alloys and composites, the in situ processed and extruded Al/AlN composite showed better creep performance with improved young's modulus, ultimate tensile strength and considerable ductility. These properties make it a useful material for a load-bearing structural composite [63] like roller bearing. Mohanavel et al. [64] recorded an increased microhardness, flexural and tensile strength of Al/AlN composite when the percentage weight fraction of AlN reinforcement was increased to 12%. The excellent thermal and mechanical properties of Al/AlN enumerated herein indicate that it is a choice composite for high temperature/high strength applications like aeroplane nozzles, electronic packaging and supercapacitors.

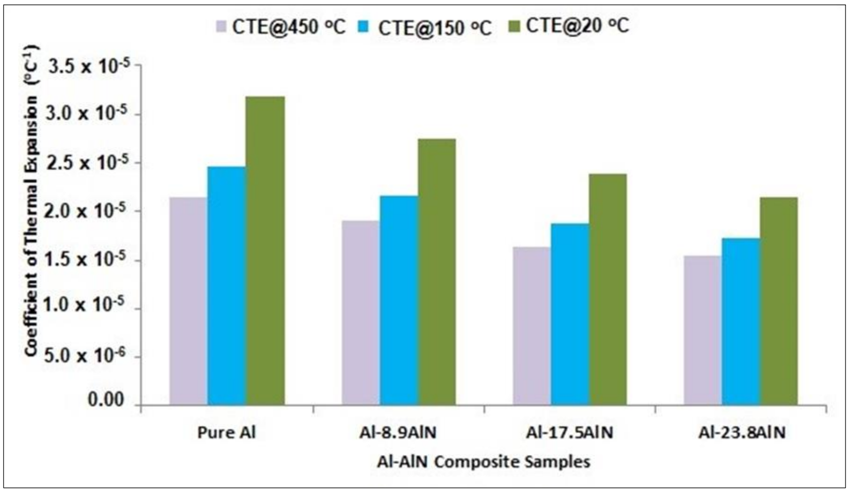

Figure 3. Profiles of volume fractions of AlN in Al against CTE at various temperatures, adapted from [61].

(iii) Al-ZrO_2 Composite: Zirconia is generally used for the development of dental implants because of its high hardness, chemical unreactivity, and biocompatibility [65]. Besides the biological application of ZrO_2, there are other industrial applications as a consequence of its excellent mechanical, tribological and corrosion properties. Such properties include high resistance to corrosion and chemical attacks, lack of usual brittleness of most ceramics, high ambient temperature strength, high fracture toughness, high wear resistance, excellent tribological characteristics, low thermal conductivity and high electrical insulation properties [66,67]. Some industrial applications of ZrO_2 are as follows: it is used for fluid handling; for development of aerospace special parts; for cutting tools; for micro-engineering; for production of electronics/electrical parts; for fibre optics; and for production of spraying nozzles [68,69]. Therefore, ZrO_2 is another excellent ceramic used for reinforcing the Al matrix that enhances its mechanical, tribological and thermal properties. In terms of tribological enhancement, Pal et al. [70] reported a 63.91% increment in wear resistance when 6 wt.% of ZrO_2 was dispersed on the Al matrix. Corrosion resistance increased from 30% to 70% (133.33%) when zirconia addition rose from 0 to 6 wt.%, and the hardness increased from 84.7 to 92.7 HRB (9.45% improvement) as shown in Figure 4. Therefore, zirconia reinforcement improves mechanical, tribological and corrosion properties of the Al alloy.

Besides increasing the wear resistance, Mazaheri et al. [71] recorded reduction of coefficient of friction from 0.55 to 0.22 by the addition of ZrO_2. Some authors reported that improvement of tribological properties was usually stimulated by uniform dispersion of ZrO_2 on the matrix as well as maintaining strong interfacial bonding [72]. ZrO_2 reinforcement has recorded tremendous improvement of the mechanical properties of Al matrix over these years. In 2008, Baghchesara et al. [73] studied the mechanical properties and surfaces fracture of an Al/ZrO_2 composite via vortex or direct incorporation method. It was observed that the UTS of the composite with 15 vol.% ZrO_2 prepared at 750 °C increased from 145 MPa to 232 MPa, while the hardness increased from 45 Brinell to 64 Brinell. However, the composite displayed a brittle fracture without necking. Later on, in 2018, James et al. [74] studied the effect of zirconia reinforcement on an Al matrix via stir casting. It was observed that addition of 5 wt.% ZrO_2 in Al6061 increased the maximum ultimate tensile strength (UTS) to 227.332 MPa, the yield strength to 196.92 MPa, and the percentage elongation to 14.28. However, the same quantity of alumina (5 wt.% Al_2O_3) into Al6061 alloy increased the ultimate tensile strength to 181.36 MPa, the yield stress to 139.65 MPa, and percentage elongation to 8.57. Thus demonstrating that zirconia improves the mechanical properties of Al more than alumina. Even though zirconia reinforcement enhances mechanical properties, but optimizing the volume fraction is of great importance. It was reported that Abdizadeh et al. [75] recorded a continuous increase in the UTS of an Al/ZrO_2 composite when the volume fraction of zirconia increased from 5 vol.% to 10 vol.%, but discovered a decrease when the volume fraction got to 15 vol.% due to the increased porosity in the microstructure. An author reported that 6 vol.% of ZrO_2 reinforcement was the optimal value [76], while Yadav et al. [77] gave 6 wt.% as the optimal concentration of zirconia in Al. By and large, Al/ZrO_2 is a prospective choice material for production of high wear resistant materials like cutting tools.

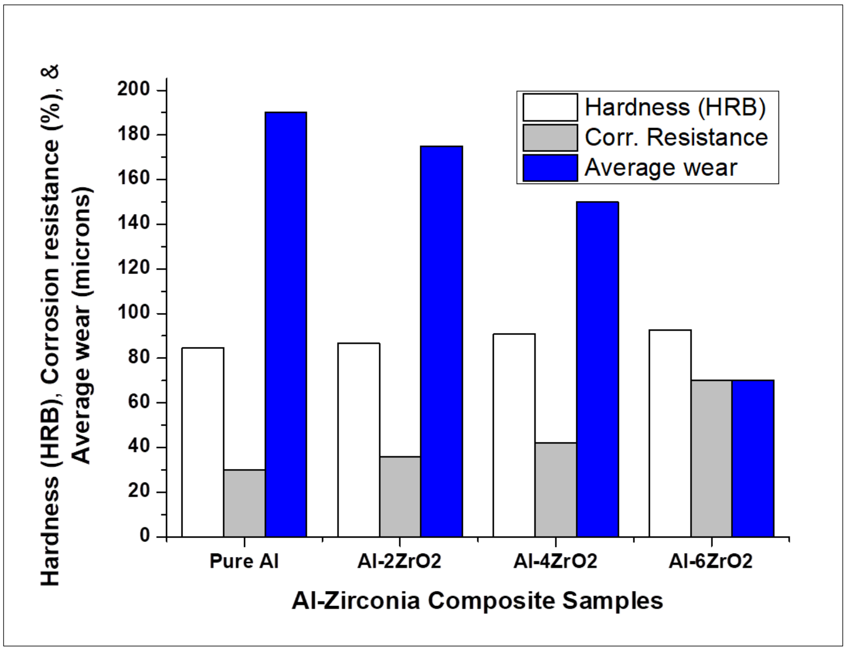

Figure 4. Property improvements of zirconia dispersion on Al matrix, adapted from [70].

(iv) Al-SiC Composite: Silicon carbide is a very popular ceramic used as an abrasive due to its wear resistance, durability and cost effectiveness. It is useful in the production of automotive brakes and clutches, and bullet proof vests due to its high abrasive properties [78,79]. SiC is one of the ceramic materials that exhibit excellent corrosion resistance together with high thermal stability that retains strength up to 1400 °C [80]. It has good electrical properties as well. As a result of all these attributes, reinforcing Al with SiC has attracted much attention. The tribological effect of SiC on an Al matrix was studied by Patel et al., [81]. It was observed that at all the applied loads, the abrasive weight loss, abrasive wear rate, and COF of the unreinforced AA5052 were higher than those of AA5052 + 5% SiC-p composite. In another study, the mechanical properties of Al/SiC were investigated. A bending strength of 294.3 MPa was recorded, while the hardness increased from 20 Hv for the unreinforced Al to 55.43 Hv for Al-20 vol.% SiC [80]. Kumar et al. [82] studied the effect of process parameters of stir casting on the enhancement of dispersion rate and mechanical properties Al/SiC. A blade angle of 45°, impeller position of 40% from the base, stirring speed of 250 rpm and melt viscosity of 1.13 mPa·s at stirring of 750 °C gave the optimum dispersion of the SiC. At these optimum parameters, the tensile strength increased by 4%, wear resistance increased by 21%, with a uniform hardness value of 47 VHN. Soltani et al. [83] studied the effect of stir casting temperature on the mechanical and microstructural properties of Al-3SiC composite. It was observed that at 680 °C stirring temperature, the UTS and yield strength were at a maximum value of 130 MPa and 90 MPa, respectively; but decreased to 110 MPa and 75 MPa, respectively, when the temperature was raised to 850 °C. The decrease in properties was attributed to the formation of shrinkage porosity and increased formation of Al4C3 at the Al–SiC interface. Meanwhile, the microhardness and elastic modulus of sample stirred at 850 °C were higher than that stirred at 680 °C. Their values were 95 MPa against 80 MPa for microhardness and 77 MPa against 76 MPa for elastic modulus. A mechanical property of the Al/SiC composite was further studied using an AA6061 matrix with SiC reinforcement of 0, 5, 10 and 15 wt.% consolidated via stir casting. The hardness and tensile strength were improved by 133.33% and 65.2%, respectively, at 15 wt.% SiC [84]. Several studies have confirmed property improvement via SiC reinforcement, which is dependent on the volume fraction and the dispersion rate of the reinforcement. Nirala et al. [85] discovered that the addition of SiC up to 15 wt.% improved the wear, mechanical and corrosion properties of Al/SiC composite. However, when this range was exceeded, those properties diminished. SiC particulates enhance the corrosion resistance of Al/SiC composite. By increasing its volume fraction or reducing its particle size, the corrosion resistance of Al/SiC was found to be better than that of the monolithic Al alloy at ambient temperature. However, at elevated temperatures (50 °C and 75 °C), the corrosion resistance became lower [86]. In another study, it was observed that the corrosion resistance of the Al matrix increased when SiC nanoparticles were incorporated through increasing the overall electron work function (EWF) of the Al-SiC nanocomposite with a subsequent increase in the corrosion potential [87]. Hence, application of an Al/SiC composite in a corrosive industrial environment is not only adequate but timely.

(v) Al-Si_3N_4 Composite: Silicon nitride (Si_3N_4) was invented in the 1960s and 1970s during the search for fully dense, high strength and high toughness materials, which it has come to represent [88]. The primary aim of its invention was to develop a ceramic material that can replace metal in advanced turbine and reciprocating engines for higher thermal stability and efficiencies. It is used in industrial applications like engine components, bearings and cutting tools [89]. A silicon nitride ceramic has high temperature stability, which is controlled by the amorphous or partially crystalline grain boundary phase; and its full densification can be achieved via liquid-phase sintering. It crystallizes into two crystals, namely: the trigonal α-Si_3N_4 and the hexagonal β-Si_3N_4. The α-modified crystal is the major material formed during powder synthesis, which transforms at higher temperatures in the presence of a liquid phase into the stable β-phase [90]. The addition of Si_3N_4 to an Al matrix has enhanced the principal properties deficient in monolithic Al alloy. Haq et al. [91] studied the dry sliding friction and wear behaviour of an AA7075-Si_3N_4 composite. It was observed that the hardness and compressive strength increased when the weight fraction of Si_3N_4 increased to 8 wt.%. At that percentage of reinforcement, a 20% improvement in hardness and 50% improvement in compressive strength were recorded. That reinforcement improved the wear resistance by 37% at 10 N loading, and 61% at 50 N loading. The COF increased initially when the weight fraction of the reinforcement was increased to 4 wt.%, beyond which it started decreasing. In another study, the hardness, yield and compressive strengths of Al-3Si_3N_4 nanocomposite increased from 38 $\pm$ 3 Hv to 77 $\pm$ 2 Hv, 70 $\pm$ 4 MPa to 127 $\pm$ 4 MPa, 305 $\pm$ 3 MPa to 364 $\pm$ 2 MPa, respectively, representing 102.6%, 81.4% and 19.3% improvements over monolithic Al [92]. Mohanavel et al. [93] investigated the microstructural and tribological characteristics of AA6351/Si_3N_4 composites manufactured by stir casting. The microhardness increased from 67 VHN at 0 wt.% Si_3N_4 to 94 VHN at 3 wt.% Si_3N_4 (40.3%); the tensile strength improved by 57.89%; the compressive strength improved from 180 MPa to 230 MPa (27.78%); the impact strength improved from 4 MPa to 9 MPa (125% improvement); percentage elongation to failure decreased from 8.6% to 6.8% (26.5% improvement); and wear rate decreased from 11.5 mm^3/m to 4.8 mm^3/m at 35 N loading (139.6% improvement). All the improvements were attributed to the grain refinement of Si_3N_4 and high bonding in the matrix/reinforcement interface. The special properties of this reinforcement are evidenced in the way it improves both the impact and elongation properties of Al alloy. This is unlike most ceramics that reduce the impact strength and elongation of the composite. Therefore, this composite is a perfect choice for reciprocating engines where high toughness, high fatigue strength, and high impact strength are of utmost importance.

(vi) Al-BN Composite: Boron nitride (BN) is a ceramic with excellent thermal and mechanical properties. It has high thermal conductivity, low thermal expansion, noble thermal shock resistance, microwave transparency, non-toxicity, high machinability, chemically inert and non-wetting by most molten metals [94]. It is a good reinforcing material for Al alloy. Firestein et al. [95] observed that when 4.5 wt.% of BN was dispersed on the Al matrix, there was a 75% increase in tensile strength, and a 190% increase in yield strength with the exhibition of ample plastic deformation. In another study, it was confirmed that an addition of 4 wt.% of BN into an Al matrix increased the tensile strength from 212 to 333 MPa (57% improvement) and hardness by 90 % [96]. There were 90% [97] and 130% [98] improvements in the ultimate tensile strength of Al-5 wt.% BN prepared through powder metallurgy; but it was reduced to 50% [95] when the percentage weight of BN decreased to 4.5 wt.%. Reddy et al. [99] investigated the enhancement of Al with BN ceramic. The results showed that the tensile strength improved by 36% when 1.5 vol.% BN reinforcement was dispersed on Al matrix, and this was attributed to the dispersion hardening of BN nanoparticles. The CTE decreased with the increasing amount of BN as a result of innate low CTE of BN nanoparticles. The addition of 1.5 vol.% BN nanoparticles improved the damping characteristics of the Al matrix. It was concluded that the Al-1.5 vol.% BN composite was a good material for weight-sensitive industrial applications. Gostariani et al. [96] worked on consolidation of Al/BN with planetary ball milling and hot extrusion using 1, 2 and 4 wt.% BN. The tensile strength improved by 40% with 1 wt.% BN, 56% with 2 wt.%, and 57% with 4 wt.% BN. The hardness increased to 102 Hv (55% improvement), 112 Hv (70% improvement) and 124 Hv (90% improvement) when compared with pure Al with the addition of 1, 2 and 4 wt.% BN. These improvements were attributed to grain refinement, formation of the in situ phase and solid solution strengthening effects of BN. There was a significant reduction in the CTE of Al/BN when 3 wt.% BN was incorporated in the Al matrix [100]. Therefore, BN is a choice ceramic for improving the mechanical and thermal properties of Al alloy; while an Al/BN composite is a choice material for the development of thermal sensitive components like bridges and rails that require low CTE and high thermal shock absorption.

(vii) Al-B4C Composite: Boron carbide (B4C) is a refractory ceramic which has high melting temperature and thermal stability; it is used as abrasive powders and coatings because it has high abrasion resistance; it has high ballistic performance because of its extreme hardness and low density; and it is utilized in nuclear applications as a neutron radiation absorbent [101]. It is a good semiconductor for electronic applications [102]. In fact, B4C is one of the hardest materials known, being third behind diamond and cubic boron nitride. As a result of its abrasive resistance, it is used in the production of nozzles for slurry pumps [103]. In order to improve the mechanical properties of Al alloy, 10, 15, 20 and 25 wt.% B4C were incorporated into Al matrices. It was observed that the UTS and YS increased as the reinforcement increased while the percentage elongation decreased. Al6061/10B4C and Al6061/20B4C gave UTS of 206 MPa and 416 MPa; and YS of 101 MPa and 369 MPa, respectively [104]. Additionally, Al2124/15B4C and Al2124/25B4C generated UTS of 421 MPa and 511 MPa; and YS of 315 MPa and 381 MPa, respectively. Shorowordi et al. [105] conducted a comparison test between Al-SiC and Al-B4C. It was observed that the wear rate and friction coefficient of Al–B4C were lower than those of Al–SiC. Wu et al. [106] investigated the effect of plasma activated sintering parameters on the microstructure and mechanical properties of an Al7075/B4C composite sintered at 530 °C for 3 min. It was discovered that the Vickers hardness was 181.6 HV, bending strength was 1100.3 MPa, compression yield strength was 878.0 MPa and the fracture strength was

469.3 MPa. The improvements were attributed to a fully densified microstructure and strong bonding of the matrix/reinforcement interface. Auradi et al. [107] consolidated an Al6061-11wt.%B4C composite via a conventional melt stirring method. The results showed that the mechanical properties (hardness, yield stress, UTS) of the composite were higher than those of the Al matrix. Ductility was the only property that decreased. The YS and UTS improved by 44.35% and 42.6%, respectively. In a functionally graded material experiment using Al/B4C composite, it was found that the hardness gradually changed from 165 BHN in aluminium region to 250 BHN in B4C region, showing that B4C region possessed higher mechanical strength [108]. Isfahani et al. [109] carried out investigation of the effect of boron carbide nanoparticles on the structural, electrical and mechanical properties of Al-B4C nanocomposites via ball milling and sintering in argon environment. By consolidating pure Al, Al-5 wt.% B4C, Al-10 wt.% B4C, the hardnesses obtained were 67 HV, 138 HV and 172 HV, respectively. This shows that by increasing the weight fraction of B4C, the hardness increased. The electrical conductivity decreased from 39% IACS for pure Al to 23% IACS for Al-5B4C and 13% IACS for Al-10B4C, which was attributed to the difference in particle size of the composite relative to pure alloy. In investigating the wear characteristics of B4C, Al-7.5 vol.% B4C and Al-15 vol.% B4C were consolidated with milling and hot extrusion. The wear rate decreased by 42.9% and 81.8%, respectively, as 7.5 vol.% and 15 vol.% B4C were incorporated into the Al matrix. From the foregoing, it can be seen that the Al/B4C composite is a choice material for developing abrasives and nozzles.

(viii) Al-CNTs Composite: In 1991, Iijima [110] detected for the first time carbon structures that existed in tubular form. It was comprised of several tens of graphitic shells that were later on called multi-walled carbon nanotubes (MWNTs). They possessed adjacent wall separation of about 0.34 nm, diameters of 1 nm and a very large aspect ratio (length/diameter ratio). However, two years later, Iijima and Ichihashi [111] as well as Bethune et al. [112] produced single-walled carbon nanotubes (SWNTs). Carbon nanotubes (CNTs) are the stiffest known material and buckle elastically (or fracture) under large bending or compressive load [113]. It has high tensile strength and elastic modulus of 100 GPa and 1.27 TPa [114], respectively; thermal conductivity of 2000 W/mK [115]; current density of 1015 A/m^2 and conductance of 13 kΩ^{-1} [116]. Besides their good mechanical and thermal properties, CNTs have large surface-to-volume ratios, high biocompatibility, and excellent optical properties. Based on the special characteristics that CNTs have, it is a very good reinforcement for the Al matrix for medical, electrical, structural, aerospace, automotive and pharmaceutical applications. The weight fraction of both SWCNTs and MWCNTs has a substantial consequence on the properties of Al-reinforced composites. When the percentage fraction increases, wettability and dispersion decrease with subsequent agglomeration which brings about severe plastic deformation [117]. It was reported that when CNTs incorporation exceeds 2 wt.%, agglomeration set in [118]. It was equally reported that for effective improvement in electrical conductivity of Al-CNTs, the reinforcement should not exceed 0.75 vol.% [119]. The effect of aspects ratio was studied and it was found that CNTs with large aspect ratio entangle easily, causing irregular dispersion of reinforcement and pronounced micro pores in the composite [120]. A comparative study to determine the best carbon reinforcements for the Al matrix was carried out by Sahoo et al. [121]. The variety of carbon materials used included MWCNT, graphene nanoparticles, graphite flakes, and ball-milled graphite. The results showed that the particle with a smaller size and higher aspect ratio enhanced the grain structure more, and had more internal transfer of shear stress. Among the whole reinforcements tested, CNTs generated the highest Young's modulus and hardness, with values of 90 and 3.5 GPa, respectively. In order to keep the weight fraction of CNTs low so as to avoid agglomeration, Park et al. [122] employed 0.1, 0.2, 0.3, and 0.4 wt.% of CNTs on the Al matrix and consolidated them via powder metallurgy technique. The yield strength and tensile strength of the composites increased as the reinforcement was increased up to 0.2 wt.% CNTs, after which the mechanical strength decreased. The best sample, Al-0.2 wt.% CNTs had yield strength and tensile strength of 90 and 114 MPa, respectively, as against pure Al, which had 56 and 92 MPa, respectively. This was an improvement of 60% and 23% in the yield strength and tensile strength. The improvements were attributed to high temperature sintering, which stimulated the development of strong interfacial bond between Al and CNT. Improvements in the corrosion rate and microhardness of Al/CNTs were recorded when 0, 1, 4 and 8 wt.% CNTs were used to reinforce Al1000 [17]. The composite was consolidated via spark plasma sintering after blending with turbular mixer. Al-4CNTs was the best sample that yielded a microhardness of 482.60 $\pm$ 12 MPa, which represented a 27% increment against the pure Al. The corrosion rate decreased by 46% and 47% in NaCl and H2SO4 media, respectively. Additionally, 8 wt.% CNTs produced poor mechanical and corrosion characteristics due to the agglomeration effect of high volume CNTs. The improvements were attributed to grain refinement, high densification and strong interfacial bonding between Al and CNTs. The strengthening mechanisms in Al/CNTs composites are stimulated by the generation of dislocations interlock as a consequence of thermal mismatch between the matrix and reinforcement since their CTEs are far apart. Also contributing to the strength is precipitation hardening through the Orowan looping mechanism, and thorough dispersion in the matrix to enhance grain boundary bridging [123]. More so, it has been reported that the elastic modulus of Al/CNTs is usually enhanced as a result of the high tensile modulus of carbon nanotubes [124]. Due to the light weight of the Al/CNTs composite, high modulus, high thermal and electrical conductivity, it is a prospective material for overhead electricity conductors.

(ix) Al-WC Composite: Tungsten carbide (WC) has a level of hardness that is second to diamond, with a Mohs hardness of 9. It retains its strength at high temperatures with low CTE, which makes it one of the best candidates for developing cutting tools that can function at elevated temperature and high-speed devices. WC is extremely stable and has high corrosion and wear resistance [125]. Krishna et al. [126] investigated the effect of WC addition on the Al matrix. By using a stir casting method, and percentage weight fraction of 1–5% of WC, the hardness, ultimate tensile strength, yield strength and wear resistance increased as the weight fraction increased up to 4 wt.% and decreased as shown in Figure 5. The UTS improved by 60.7%, YS improved by 95.5%, hardness (Hv) improved by 78.6%, while the wear rate improved by 6900%. The high improvement in the wear resistance made the authors recommend the composite for brake rotor discs. The decline of properties when the weight percentage exceeded 4% was attributed to insufficient wettability. In another study, Megahed et al. [127] used friction stir processing to consolidate Al-WC. It was observed that Al-6 vol.% WC was the best composite in terms of high strength at elevated temperature applications. The mechanical, corrosion and wear resistance were all improved. Therefore, Al/WC composite is a choice composite for cutting tool blades, rotors and abrasives.

(x) Al-TiC Composite: TiC is an excellent ceramic suitable for improving the properties of Al alloy by boosting its thermal, mechanical, tribological and corrosion properties. Raviraj et al. [128] studied the effect of TiC addition on Al matrix. It was discovered that by the addition of 5 wt.% of TiC, the yield strength, modulus of elasticity, microhardness and percentage elongation improved by 88%, 21.6%, 20.3% and 52.4%, respectively. Bauri et al. [129] recorded 40% increase in ultimate tensile strength and 52.6% increase in microhardness of Al-TiC prepared via double pass friction stir processing (FSP). There was tremendous improvement in the tribological properties of Al-TiC composite when the weight fraction of TiC was 7.5 wt.% [130]. Wang et al. [131] studied the effect of TiC on the mechanical properties of Al alloy. It was observed that addition of 0.5 wt.% TiC improved the yield strength, ultimate tensile strength and percentage elongation by 117.3%, 40% and 81.3%, respectively. It can be seen that Al-TiC has excellent properties and so has high industrial value.

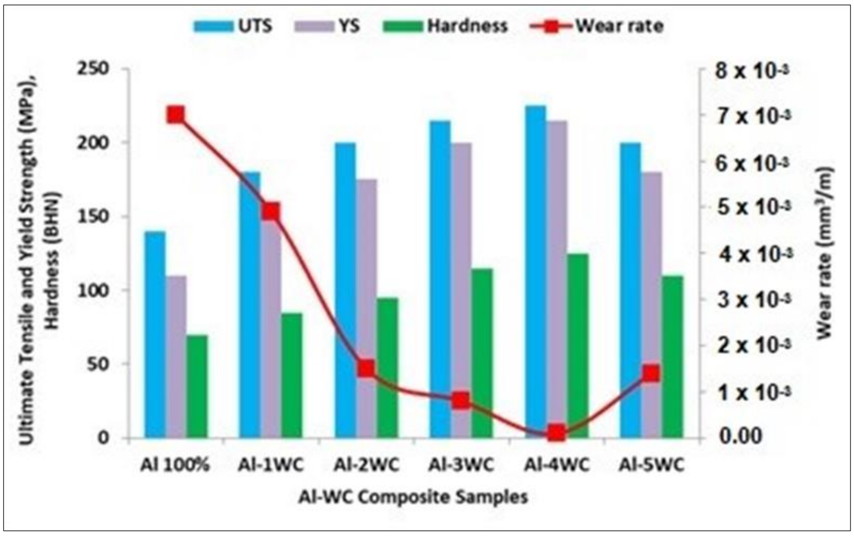

Figure 5. Mechanical and tribological characteristics of Al-WC, adapted from [126].

2.2. Aluminium Hybrid Composite System

Sometimes, a single reinforcement may not give the required properties for specific applications in a metal matrix composite system. In that case, two or more different reinforcements will be alloyed to generate a hybrid composite system. Studies have shown that hybrid composite systems possess better properties than conventional composites [132]. The advantages of hybrid composites over conventional composites include balanced strength and stiffness, balanced bending strength, superior mechanical properties, high and stable thermal resistance, low weight, reduced cost, better fatigue resistance, decreased notch sensitivity, enhanced fracture toughness and crack attenuation capability with enhanced impact resistance [133,134]. Akinwamide et al. [135] worked on microstructural, mechanical and tribological properties of stir cast binary and ternary aluminium based composites. The wear rate results are shown in Figure 6.

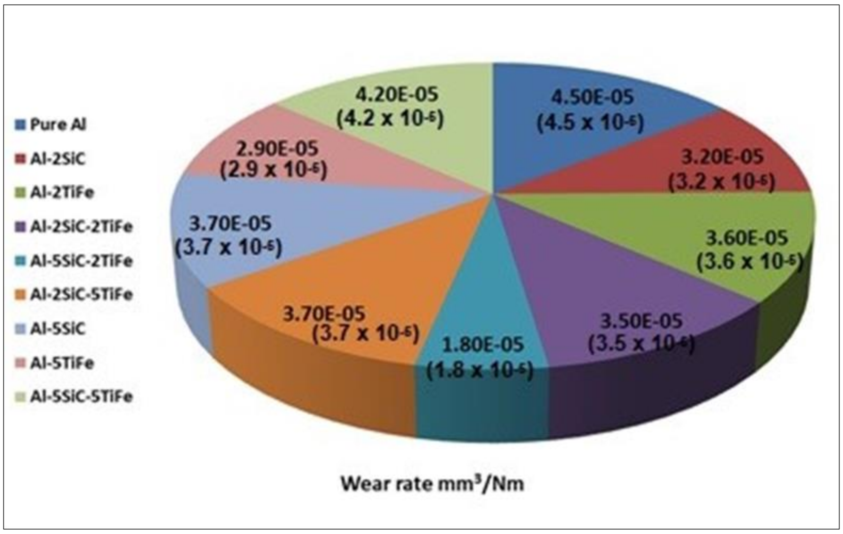

Figure 6. Wear rates of pure Al, Al-SiC, Al-TiFe and Al-SiC-TiFe composites, adapted from [135].

The composites developed included Al-SiC, Al-TiFe and Al-SiC-TiFe. They were characterized, and the results showed that Al-5TiFe had the highest yield strength of 115 MPa, highest ultimate tensile strength of 141 MPa and percentage elongation of 7.6%. The improvement was attributed to the high Fe content in the composite, which is a renowned strengthening metal. Another sample with improved properties was Al-2% SiC-5% TiFe, which had a yield strength of 94 MPa, UTS of 116 and elongation of 1.6%. Al alloy had YS of 69 MPa, UTS of 82 MPa and elongation of 4.2%. Hence, the best sample had improvements of 66.7% and 72% in YS and UTS, respectively. Al alloy possessed the highest wear rate of 4.5×10^{-5} mm^3/Nm, while Al-5% SiC-2% TiFe had the lowest wear rate of 1.8×10^{-5} mm^3/Nm (150% improvement), while Al–5TiFe had a wear rate of 2.9×10^{-5} mm^3/Nm (55.2%) as shown in Figure 6. This study has shown that a ternary composite system is not always better than a binary composite system in all the properties. Sometimes a binary system may have more improved properties than the ternary or hybrid composite system. Therefore, adequate care and skill must be employed in choosing the reinforcing phases adequate for generating target properties. Some recently developed hybrid composites of Al are summarized in Table 2.

Table 2. Properties of aluminium hybrid composite systems.

Composite	Technique	Properties (Percent Improvement)	Remarks	Ref.
a. A7075-10B_4C-5Gr b. A6061-10B_4C-5Gr	i. liquid casting ii. liquid casting	a. Hv: 120 Hb (9%) b. Hv: 108 Hb (8%) a. WR: 0.018 mg/m (233%) b. WR: 0.02mg/m (300%) a. TS: 230 MPa (10%) b. TS: 180 MPa (13%)	The elongation to failure was lower in A7075 than A6061. The improvements were attributed to the resistance to indentation and stress of the reinforcements, especially B4C.	[136]
Al-9Al_2O_3-3Gr	Stir casting	Hv: 94 Hb (20%) TS: 201 MPa (32%) Shear:142.3 Nmm^{-2} (25%)	Hard alumina and soft graphite particles influenced property improvement. The formation of mechanically mixed layer (MML) improved the wear properties of the composite	[137]
Al-3B4C-5MoS4	Stir casting	Hv: 101 Hb (24%) Elongation: 2.95 (31%) TS and YS decreased by 38%. Wear rate decreased with increase in reinforcement	The ductility, tensile and yield strengths of the composite decreased as the reinforcement increased from 3 to 5% because of ineffective transfer of load by the reinforcements; and the formation of void at matrix reinforcement interface.	[138]
Al-5CNTs-10SiC	SPS	Hv: 158 HV (172%)	The authors predicted that the composite will possess high wear resistance. The dislocation defect was highly reduced in the composite. Further increase in CNTs concentration resulted in their agglomeration.	[139]
Al-15SiC-5TiC	SPS	Hv: 3060 MPa Bending: 312 MPa	When the authors compared SPS with conventional sintering, SPS gave better properties. Density generated by SPS and conventional sintering were 99.2 ± 0.4% and 90.4 ± 0.7%, respectively.	[140]
Al-10Zn-5Sn	SPS	Hv: 572.92 MPa TS: 188.08 MPa	The hardness/tensile data confirmed that the composite is good for replacing Pb solder.	[141]

Table 2. *Cont.*

Composite	Technique	Properties (Percent Improvement)	Remarks	Ref.
Al-10SiC-4 Kaolin	SPS	TS: 263 MPa (13.3%) Compressive strength: 282 MPa (11.7%) Hv: 147 VHN (16.3%)	The authors compared SPS with conventional sintering (CS) and observed that the high sintering time in CS leads to the formation of detrimental Al2Cu intermetallic, which makes the composite brittle.	[142]
Al-10SiC-10FlyAsh	Conventional sintering	Hv: 62 HR (32%) Wear loss: 0.0017 g (65%)	The composite had improved hardness and wear resistance, which were attributed to restriction of dislocation and plastic deformation by the dispersed phases.	[143]
Al-10SiC-5TiB_2	Cold compaction and sintering	TS: 230 MPa (64%) YS: 125 MPa (23%) Elong: 2.5% (100%)	The low elongation recorded in the composite resulted in brittle fracture during tensile test, which was attributed to cracks and debonding effects of SiC particles.	[144]
Al-9SiC-2Al_2O_3	Stir casting	TS: 325 MPa YS: 107 MPa Elong: 2.08% Hv: 119 VHN	The presence of SiC and Al_2O_3 induced brittle fracture in the composite.	[145]
Al-20Al_2O_3-3Gr	Stir casting	TS: 230 MPa (73%) Flexural: 427.43 MPa (72%) Hv: 95 HV (38%)	The increase in strength was attributed to the resistance to plastic deformation, particle strengthening and grain refinement effects of the reinforcements.	[146]
Al-5SiC-9ZrO_2	Green compact sintering	Hv: 59 RHN (43%) Wear loss: 0.004 g (100%)	The superior wear characteristics of this composite was attributed to the load-bearing capacity of ZrO_2.	[147]
Al-7.5B4C-2.5Cow dung ash (CDA)	Double stir casting	Hv:145 BHN (32%) TS: 280 MPa (56%) Wear rate: 0.002 mm^3/m (150%)	The impact strength decreased in the composite as compared to base metal because of reduced ductility of the composite. The presence of soft CDA in the composite improved its elongation to failure.	[148]
Al-2.5Groundnut shell ash-7.5B4C	Squeeze casting	Hv: 115 BHN (17%) TS: 348.45 MPa (18%) YS: 285 MPa (14.77%)	The addition of the GSA decreased the impact strength which resulted to cracks, brittle fracture and fractured particles in the composite.	[149]
Al-5Gr-4TiC	Stir casting	Hv: 142 HV TS: 225 MPa	The improvement in the mechanical properties was a result of increase in dislocation density around the matrix-reinforcement interface and grain refining of the composite.	[150]

2.3. Aluminium Matrix Reinforced with Nano-Sized Reinforcements

Nanoparticles (0D), nanorods/nanofibers (1D), and nanosheets (2D) are the various nano-sized reinforcements presently researched for the improvement of the properties of Al matrix. Reinforcements in the nanoscale structure are preferred to micro-meter counterparts because they are lighter in weight; they possess higher volume-to-surface ratios with diameters that are more controllable; they exhibit higher reactivity; and they enhance material properties more [151]. Therefore, the applications of Al matrix composites have received substantial expansion and advancement since the introduction of nano-sized reinforcements. Some authors have reported better fatigue and tensile strengths; higher hardness, better tribological, chemical and thermal properties [152] when nanoparticles were used to reinforce Al matrix. In order to harness the plethora of advantages obtainable in reinforcing Al matrices with nanomaterials, the volume fraction must be controlled because too much of the nanomaterials induce agglomeration and poor wettability. When ceramic nanofibers (1D) were used to reinforce an Al/Mg matrix in a study, it was observed that when the volume fraction exceeded 1%, the mechanical strength and other properties deteriorated, which was attributed to the dwindling of the crack bridging effect of the nanofibers/weak interfacial bonding between nanofibers and the Al/Mg composite. However, below 1%, the properties improved tremendously [153]. It was reported that the thermal conductivity of an Al matrix reinforced with graphene nanosheets (2D) and SiC nanorods (1D) increased by 115%, making the composite suitable for aerial conductors as well as other thermal applications [154]. With 46% improvement in corrosion resistance in NaCl medium and 47% improvement in H_2SO_4 medium, Al reinforced with CNTs (1D) and produced with SPS was suggested to be a useful material for overhead electrical transmission conductors, especially in corrosive environments [17]. By and large, the introduction of nano-sized reinforcements to metal matrices has expanded the usefulness of AMCs; even though their homogenous dispersion into the matrix together with their wettability needs further research.

3. Techniques for the Development of AMCs

AMCs are majorly processed through two techniques, the solid and liquid methods [43]. The solid route makes use of powder metallurgy (PM), while liquid method can come in the form of a compo-casting, squeeze casting or stir casting technique [155]. Powder metallurgy is a very important technique in the development of binary and hybrid AMCs since composites with high weight fractions of reinforcements can easily be developed with it [156]. More so, hybrid AMCs that are reinforced with nanoparticles can equally be fabricated with this method [157], but it is difficult with other methods. PM has gained a lot of attention because particle agglomeration, poor wettability and evolution of deleterious secondary phases that accompany liquid technique are absent in it [52,158]. Sintering is the major technique used in compacting powders in PM. There exists pressureless and pressure-assisted sintering. One of the most advanced pressure assisted sintering that ensures zero contamination of composites is called high-frequency induction heat sintering (HFIHS). This involves heating of green compacts or powder samples via high frequency induction heating with the application of pressure. One of the main advantages is that there is no physical contact between the heating coil and the sample as shown in Figure 7, thereby ensuring non-contamination of the sample. It is time saving, energy conserving, and grain refining. In an experiment to compare conventional sintering with high-frequency induction heat sintering, it was observed that higher densification (95%) was observed in the high-frequency induction heating than in conventional heating, which gave 80% [159]. HFIS produced samples with low oxygen contamination with zero grain growth as a result of its low sintering temperature and short dwell time [160]. Therefore, when purity of composite is required, this method is recommended.

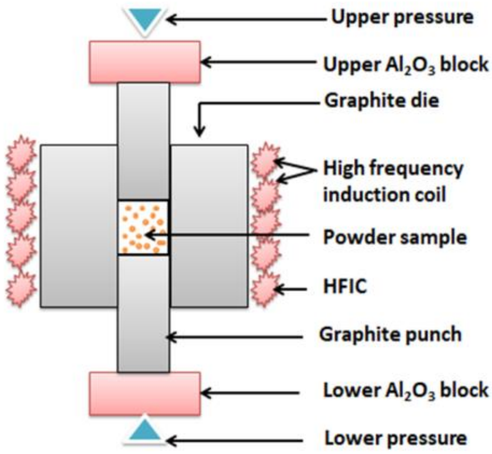

Figure 7. High frequency induction heat sintering device, adapted from [161].

Spark plasma sintering (SPS) is another advanced type of pressure-assisted, non-conventional sintering, whereby heat and pressure are applied simultaneously to achieve high densification in the composite. SPS has been adopted as a choice PM technique for the production of AMCs because of its excellent properties. It produces refined-grained composites, pure composites, and aids in homogenous dispersion of reinforcing particles. Its short sintering time reduces the formation of deleterious secondary phases in AMCs [17]. The purifying property of SPS is attributed to the pulsed direct current that generates intermittent electric sparks at the microscopic level of the powders, which vaporize impurities contained in the powders [162]. The spark produces heat that is strong enough to melt and vaporise the impurities in the powder. SPS has been reported to have enhanced the piezoelectric [163], thermoelectric [164], tribological [165], corrosion [166], mechanical [167], FCC and BCC phases evolution [168], and microstructural [169] (Figure 8) properties of MMCs. Figure 8 shows the microstructure of Al_2O_3–ZrO_2 (3Y)–SiC composite sintered at different temperatures. It can be seen that microstructure improvement is a function of the sintering temperature. At the low temperature of 1300 °C (Figure 8a), the bonding was loose and the grains are yet to refine. At the higher temperature of 1350 °C, Figure 8b, the intermolecular bonding was stronger with a finer grained microstructure. However, at a much higher temperature of 1400 °C (Figure 8c), there was grain coarsening, which negatively affected the mechanical properties. The improvements achieved with optimized sintering parameters of SPS are attributed to its high heating and cooling rates; its capacity to improve homogenous dispersion of reinforcements; its capacity to vaporize impurities; its grain refining capability; its tendency in generating high dislocation density; its ability to interlock grain boundaries; its strong metallurgical bonding capacity and stable thermodynamics and kinetics [170,171]. Even though SPS has been adopted as one of the most favourable advanced solid fabrication techniques for nanocomposites of metals, the commercial viability still needs further research.

For liquid technique, stir casting is the most researched technique for producing AMCs because of its easiness, suppleness and cost effectiveness [8,172]. Even though it faces many challenges such as non-homogenous dispersion of reinforcement, micro pores, poor wettability, agglomeration of reinforcing phases, segregation, interfacial reactions and formation of deleterious phases, techniques to ameliorate the challenges have been reported [172,173]. For instance, particle segregation and agglomeration can be ameliorated through optimizing mixing parameters like stirring speed, rotation of stirrer, blade angle to stirrer axis [173] and also by adopting a two-step stir casting technique [174,175]. Improved wettability can be obtained through reinforcement coating [176] and use of wetting agents like K2TiF6 [177], borax and magnesium [178]. For interfacial reaction and evolution of deleterious phases, the selection of non-reacting reinforcements like Al_2O_3 and B4C can ameliorate them [179]. Porosity can be reduced via adoption of hot isostatic pressing [180,181] or cold deformation [180] techniques. Stir casting and powder metallurgy have been reported to have improved strength and stiffness at the expense of ductility and toughness. The only discovered technique that does not compromise ductility and toughness is friction stir processing (FSP). Friction stir processing develops AMCs with higher surface hardness [181], improved creep resistance, high ductility and toughness [182]. It improves the dispersion of reinforcements and decreases porosity in AMCs. It is usually used in the post-fabrication process to enhance the properties of AMCs produced through powder metallurgy [183]. Moreover, nanocomposite surfaces have been produced on metallic substrates with friction stir processing [184]. However, further research is required in this area in terms of promoting its commercial viability.

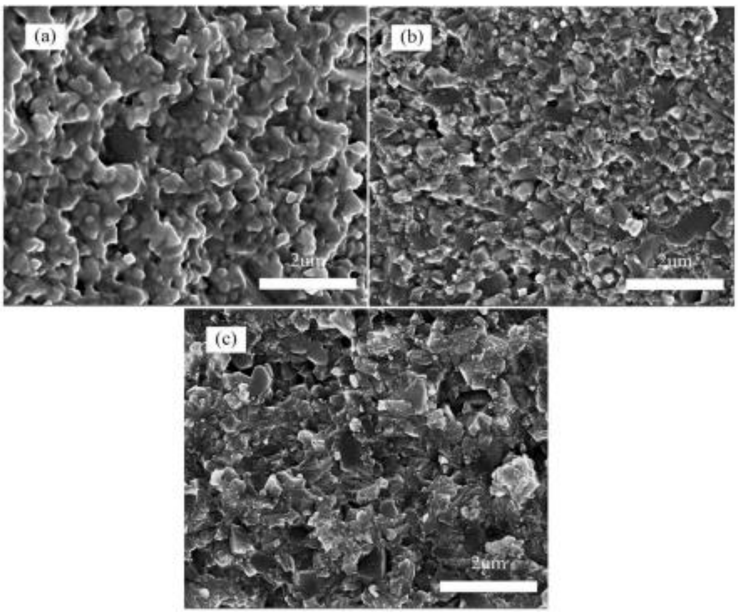

Figure 8. SEM Images of Al_2O_3–ZrO_2 (3Y)–SiC composite sintered at (**a**) 1300 °C, (**b**) 1350 °C and (**c**) 1400 °C [169].

Another liquid fabrication technique worthy of discussion is the liquid metal infiltration method. Poor wettability of reinforcement was stated as one of the challenges of stir casting together with micropores as a result of gas dissolution of the molten metal during stirring and blending. Therefore, in the liquid metal infiltration technique, the use of external force (vacuum) enhances the wettability via decreasing the wetting angle, which separates the matrix and the reinforcement [185]. Additionally, the preform enhances homogenous dispersion of reinforcements and discourages their settling at the bottom or floating on top occasioned by differences in their densities [186]. This method has been very useful in the fabrication of automotive engine blocks and brake linings.

4. Applications and Challenges of Aluminium Matrix Composites

4.1. Applications of Aluminium Matrix Composites

Monolithic Al is always a choice material when weight, ductility and availability are of utmost requirement like in aerospace, overhead conductors, and automobile industries. However, its weak strength and tribology [187]; its thermal instability, low stiffness, and low wear resistance undermines its applications. Hence, the deficient properties are augmented through the addition of reinforcements. For instance, it was reported that the elastic modulus of monolithic aluminium was enhanced from 70 GPa to 240 GPa (243% improvement) by adding 60 vol.% Al_2O_3 fibre into the matrix. Moreover, the coefficient of thermal expansion decreased from 24 to 7 ppm/°C through this reinforcement [43]. AMCs are among the most useful and most sought after MMCs in the world. Present and prospective applications of AMCs are discussed in this section.

(i) Aerospace industry: AMCs have been the composite of choice for aircraft structures of all types ever since the launch of Sputnik 1 in 4 October 1957. Its choice was based on its light weight together with its capability to withstand the stresses and impacts during launching and operation in the space. AMCs have been used on Apollo spacecraft, the Skylab, the space shuttles and the International Space Station. They out-perform other composites in this field in terms of mechanical, dampening, thermal and low weight properties [35].

(ii) Automotive industry: AMCs-based engine blocks, pistons, suspension system, body panels, frames, etc., are now being used to replace steel or cast iron-based automotive components. They are being used to replace steel components because of their reduced weight, improved yield strength and modulus. AMCs are competing vigorously to replace all the steel components in a vehicle such as valve covers, torque converter and transmission housings, crankcase, suspension links, door frames, steering wheels, dashboards and sheet panels [188]. The replacement of steel components reduces the fuel consumption, the corrosion affinity and the CTE of the vehicle parts. Modern vehicle models like Lotus Elise, General Motors EV1, Chrysler Prowler, Volkswagen Lupo 3L and Toyota RAV4 EV make use of the Al-SiC composite for brake rotors [189].

(iii) Railroad and marine cars: Cars produced with AMCs need only 0.33 of the number of components, possess decreased welding points and are only 0.67 the weight of steel cars counterpart. The fuel costs are reduced with such cars because of the lighter weight, besides the cost of corrosion control [190].

(iv) Building and construction industry: AMCs-based materials are presently being recognised as the most energy-saving and sustainable construction materials because about 85% of the aluminium used in modern buildings comes from recycling. AMCs-based bridge decks need only a minute cost of maintenance, as they have high resistance to corrosion and require no painting, quite unlike concrete. Recently developed robust AMCs can withstand the weight of heavy glass panels, which makes it possible for modern buildings to utilize natural sunlight [191].

(v) Electronic packaging and other thermal devices: Heat sinks provide two major functions in electronic packaging. They provide thermal stability through adequate heat dissipation and provide a mechanical framework. Therefore, they support electronic devices and create necessary pathways for heat removal. AMCs possess better properties such as higher thermal conductivities, lower CTE, higher weight reductions, and higher strength and stiffness than the conventional heat sinks like Cu-tungsten or Cu-Molybdenum [192,193].

(vi) Overhead electricity transmission conductors: AMCs-based conductors are lighter in weight than Cu-based composite conductors. With the reduced weight and improved thermal and electrical properties, AMCs are the choice materials for the development of advanced transmission conductors. Those present in the market and doing very well in operation include aluminium conductor composite reinforced (ACCR) and aluminium conductor composite core (ACCC), which are made of Al alloys and composites. Their performances are better than that of the conventional conductor, aluminium conductor steel reinforced (ACSR), which has a steel core that is ravaged by high weight, corrosion and high CTE [194].

(vii) Sports and recreation equipment: AMCs have come to be the choice material for the development of sports and recreation equipment. They include aluminium matrix reinforced with SiC or B4C particle. It has been reported that the specific strength and stiffness of the AMCs are higher than the conventional steel or carbon/epoxy composites that were being used. They are more cost effective too [195].

(viii) Defense application: Al matrix reinforced with fibre is one of the choicest composites for producing weapons due to its excellent properties. Traditionally, beryllium was the choice material for developing missiles, but it was reported that AMCs are being used to replace Be because they are more cost effective, and not as toxic as beryllium. Fins of a directed gun are produced with AMCs because of its rigidity and high accuracy [35].

4.2. Challenges in the Development of Aluminium Matrix Composites

(i) Agglomeration of reinforcements: Agglomeration is described as clustering/bundling or inhomogeneous dispersion of reinforcements in the matrix of a composite system. Sun et al. [196] noted that an increase of agglomerated ratio skyrockets the stress intensity in composite materials. This is because failure initiates from the interface between reinforcement and the matrix and takes place at the sharp corners of the reinforcing particles. Agglomeration of reinforcements induces porosity and subsequently weakens the mechanical, thermal and electrical properties of composite materials. It reduces mechanical properties by weakening the dislocation density; weakens thermal and electrical properties through phonon scattering effect; and it acts as a barrier to load transfer among the grains [197].

(ii) Compromising ductility and toughness with hardness and strength: The principal difference between hardness and toughness remains that they are inversely related. When the hardness increases, toughness decreases [198]. Recall that hardness is the ability of a material to resist indentation or permanent deformation, while toughness is the degree a material can undergo before permanent damage. Therefore, it is impossible to have resistance to a property and still accommodate the material. Hence, in order to improve the hardness of Al through incorporation of reinforcing particles, the ductility as well as the toughness of the Al alloy always diminishes.

(iii) High quality but high cost reinforcements: Most high quality conventional reinforcements are costly. Until cheap, sustainable and biowaste reinforcements are able to be engineered and developed to replace the conventional reinforcements, development of AMCs is endangered. The cost of agro-wastes like rice husk ash cannot be equated to SiC for instance; however, the strengthening properties of rice husk ash are not comparable to those of SiC. Therefore, research should be geared towards the development of these sustainable materials so that AMCs can be more cost effective.

(iv) Formation of deleterious intermetallic phases: One of the most cost effective fabrication techniques of AMCs is stir casting. However, one of its challenges is the formation of deleterious intermetallic compounds as was experienced in the stir casting of AA2024-Al3NiCu composite where Al3Ni was formed [199]. Other AMCs development techniques like conventional sintering also generate an intermetallic that affects the properties of the developed composites.

(v) High cost of Al: It has been reported that Al is four to five times higher than steel. Therefore, the high cost of Al is one of the challenges militating against the development of AMCs. Hence, the development of more cost effective production techniques of Al which will reduce the cost of Al is highly encouraged.

5. Conclusions and Recommendations

Recent advancements in the development of AMCs have been studied. It is concluded that:

(i) AMCs are the most highly demanded MMCs, with the advantages of high temperature of operation, non-flammability, and high resistance to degradation by organic fluids, high corrosion and wear resistance, and light weight.

(ii) Al composite binary system possesses some essential properties absent in ternary or hybrid systems. Binary systems always exhibit lower agglomeration of reinforcements as wettability is always higher. Therefore, their microstructures are always refined with improved mechanical and physical properties.

(iii) Hybrid composites are always better in terms of property improvement, but they are challenged by poor dispersion of reinforcements, poor wettability, scattered micro-pores, and weak reinforcement/matrix interface because of the weak compatibility of the two or more unrelated reinforcements. Al reinforced with nanomaterials possesses the best properties among the entire groups, though agglomeration is still their challenge.

(iv) Powder metallurgy is a very essential technique used in developing both binary and hybrid nanocomposites of Al, which other techniques cannot. SPS is regarded as the most successful type of PM technique with essential qualities, though challenged by poor commercial scalability.

(v) Stir casting is the most cost effective fabrication of AMCs; however, it is challenged by the formation of deleterious intermetallic phases, segregation, interfacial reactions, etc.; though ways of ameliorating these challenges have been reported.

(vi) Stir casting and powder metallurgy have been reported to have improved strength and stiffness at the expense of ductility and toughness. The only technique that does not compromise ductility and toughness with strength is friction stir processing (FSP).

The following recommendations are presented:

(i) To reduce agglomeration of reinforcements in AMCs, cryogenic ball milling is recommended. In situ fabrication equally enhances homogenous dispersion of reinforcements ensuring minimal agglomeration.

(ii) Techniques that can develop bulk AMCs without compromising strength with toughness should be researched further as FSP is only a surface improving procedure.

(iii) Research to develop low cost, sustainable and agro-waste reinforcement, which can compete favourably with conventional Al reinforcements is recommended.

(iv) Further research on commercial scalability of SPS is recommended since it is one of the best methods of developing AMCs without the formation of deleterious intermetallic phases.

(v) It is recommended that further research on more cost effective exploration and exploitation of Al metal alloys capable of reducing the price to be at par or even lower than steel should be carried out.

Funding: This research was funded by the National Research Foundation (NRF) of South Africa. The article publishing charges were paid for from funds received from the NRF.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge and appreciate the support received from the Faculty of Engineering and Built Environment, University of Johannesburg, South Africa.

Conflicts of Interest: There is no conflict of interest whatsoever.

References

1. Shyha, I.; Huo, D. *Advances in Machining of Composite Materials*; Springer: Cham, Switzerland, 2021.
2. Nagavally, R.R. Composite materials-history, types, fabrication techniques, advantages, and applications. *Int. J. Mech. Prod. Eng.* **2017**, *5*, 82–87.
3. Kabir, R.B.; Ferdous, N. Kevlar—The super tough fiber. *Int. J. Text. Sci.* **2012**, *1*, 78–83. [CrossRef]
4. Research. History of Composites. 2018. Available online: https://www.thoughtco.com/history-of-composites-820404#:~{}:text=He%20also%20writes%20about%20the%20industry.&text=When%20two%20or%20more%20different,create%20strong%20and%20durable%20buildings (accessed on 25 July 2022).
5. Callister, W. Composites, chapter 16. In *Material Science and Engineering an Introduction*; John Wiley and Sons, Inc: Hoboken, NJ, USA, 2003; p. 527.
6. Safri, S.N.A.; Sultan, M.T.H.; Jawaid, M.; Jayakrishna, K. Impact behaviour of hybrid composites for structural applications: A review. *Compos. Part B Eng.* **2018**, *133*, 112–121. [CrossRef]
7. Ananth, C.; Chandra, N. Elevated temperature interfacial behaviour of MMCs: A computational study. *Compos. Part A Appl. Sci. Manuf.* **1996**, *27*, 805–811. [CrossRef]
8. Kaczmar, J.; Pietrzak, K.; Włosiński, W. The production and application of metal matrix composite materials. *J. Mater. Processing Technol.* **2000**, *106*, 58–67. [CrossRef]
9. Salih, O.S.; Ou, H.; Sun, W.; McCartney, D. A review of friction stir welding of aluminium matrix composites. *Mater. Des.* **2015**, *86*, 61–71. [CrossRef]
10. Torralba, J.D.; Da Costa, C.; Velasco, F. P/M aluminum matrix composites: An overview. *J. Mater. Processing Technol.* **2003**, *133*, 203–206. [CrossRef]
11. Lloyd, D. Particle reinforced aluminium and magnesium matrix composites. *Int. mater. Rev.* **1994**, *39*, pp.1–23. [CrossRef]
12. Koli, D.K.; Agnihotri, G.; Purohit, R. Advanced aluminium matrix composites: The critical need of automotive and aerospace engineering fields. *Mater. Today Proc.* **2015**, *2*, 3032–3041. [CrossRef]

13. Singh, J.; Chauhan, A. A review on sliding wear behaviour of aluminium matrix composites with hybrid reinforcements for automotive applications. *Tribol. Online* **2014**, *9*, 121–134. [CrossRef]
14. Purohit, R.; Qureshi, M.; Jain, A. Forming behaviour of aluminium matrix nano Al_2O_3 composites for automotive applications. *Adv. Mater. Processing Technol.* **2020**, *6*, 272–283. [CrossRef]
15. Ujah, C.; Popoola, P.; Popoola, O.; Aigbodion, V. Enhanced mechanical, electrical and corrosion characteristics of Al-CNTs-Nb composite processed via spark plasma sintering for conductor core. *J. Compos. Mater.* **2019**, *53*, 0021998319848055. [CrossRef]
16. Ujah, C.; Popoola, A.; Popoola, O. Thermal conductivity improvement of Al alloy with Nb nanopowder using SPS for transmission conductor. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Boston, MA, USA, 12–14 October 2019; p. 012004.
17. Ujah, C.; Popoola, A.; Popoola, O.; Aigbodion, V.S. Influence of CNTs addition on the mechanical, microstructural, and corrosion properties of Al alloy using spark plasma sintering technique. *Int. J. Adv. Manuf. Technol.* **2020**, *106*, 2961–2969. [CrossRef]
18. Kumar, N.; Das, A. Ecofriendly energy efficient welding of aluminium matrix composites for aerospace applications: A state of art review. *Mater. Today Proc.* **2020**, *26*, 1666–1675. [CrossRef]
19. Suryanarayanan, K.; Praveen, R.; Raghuraman, S. Silicon carbide reinforced aluminium metal matrix composites for aerospace applications: A literature review. *Int. J. Innov. Res. Sci. Eng. Technol.* **2013**, *2*, 6336–6344.
20. Shibli, S.; Archana, S.; Ashraf, P.M. Development of nano cerium oxide incorporated aluminium alloy sacrificial anode for marine applications. *Corros. Sci.* **2008**, *50*, 2232–2238. [CrossRef]
21. Vinod, B.; Ramanathan, S.; Ananthi, V.; Selvakumar, N. Fabrication and characterization of organic and in-organic reinforced A356 aluminium matrix hybrid composite by improved double-stir casting. *Silicon* **2019**, *11*, 817–829. [CrossRef]
22. Hynes, N.; Sankaranarayanan, R.; Tharmaraj, R.; Pruncu, C.I.; Dispinar, D. A comparative study of the mechanical and tribological behaviours of different aluminium matrix–ceramic composites. *J. Braz. Soc. Mech. Sci. Eng.* **2019**, *41*, 330. [CrossRef]
23. Reddy, A.P.; Krishna, P.V.; Rao, R.N.; Murthy, N. Silicon carbide reinforced aluminium metal matrix nano composites—A review. *Mater. Today Proc.* **2017**, *4*, 3959–3971. [CrossRef]
24. Mohanavel, V.; Ravichandran, M.; Kumar, S.S. Tribological and mechanical properties of Zirconium Di-boride (ZrB2) particles reinforced aluminium matrix composites. *Mater. Today Proc.* **2020**, *21*, 862–864. [CrossRef]
25. Ferreira, L.; Bayraktar, E.; Robert, M. Magnetic and electrical properties of aluminium matrix composite reinforced with magnetic nano iron oxide (Fe3O4). *Adv. Mater. Processing Technol.* **2016**, *2*, 165–173. [CrossRef]
26. Ravi, B.; Balu, N.; Uday, P. Fabrication and mechanical characterization of boron carbide reinforced aluminium matrix composites. *Discovery* **2016**, *52*, 1389–1395.
27. Nagaral, M.; Auradi, V.; Ravishankar, M. Mechanical behaviour of aluminium 6061 alloy reinforced with Al_2O_3 & graphite particulate hybrid metal matrix composites. *Int. J. Res. Eng. Technol.* **2013**, *1*, 193–198.
28. Khan, M.; Zulfaqar, M.; Ali, F.; Subhani, T. Hybrid aluminium matrix composites containing boron carbide and quasicrystals: Manufacturing and characterisation. *Mater. Sci. Technol.* **2017**, *33*, 1955–1963. [CrossRef]
29. Talla, G.; Sahoo, D.K.; Gangopadhyay, S.; Biswas, C. Modeling and multi-objective optimization of powder mixed electric discharge machining process of aluminum/alumina metal matrix composite. *Eng. Sci. Technol. Int. J.* **2015**, *18*, 369–373. [CrossRef]
30. Singh, N.; Belokar, R. Tribological behavior of aluminum and magnesium-based hybrid metal matrix composites: A state-of-art review. *Mater. Today Proc.* **2021**, *44*, 460–466. [CrossRef]
31. Mavhungu, S.; Akinlabi, E.; Onitiri, M.; Varachia, F. Aluminum matrix composites for industrial use: Advances and trends. *Procedia Manuf.* **2017**, *7*, 178–182. [CrossRef]
32. Macke, A.; Schultz, B.; Rohatgi, P. Metal matrix composites. *Adv. Mater. Processes* **2012**, *170*, 19–23.
33. Stojanović, B.; Ivanović, L. Application of aluminium hybrid composites in automotive industry. *Tehnički Vjesnik* **2005**, *22*, 247–251. [CrossRef]
34. Chawla, K.K.; Chawla, N. Metal matrix composites: Automotive applications. *Encycl. Automot. Eng.* **2014**, 1–6. [CrossRef]
35. Nturanabo, F.; Masu, L.; Kirabira, J.B. *Novel Applications of Aluminium Metal Matrix Composites*; University of Bradford: Bradford, UK, 2019; pp. 1–25. [CrossRef]
36. Kar, K.K. *Composite Materials: Processing, Applications, Characterizations*; Springer: Berlin/Heidelberg, Germany, 2016.
37. Dokšanović, T.; Džeba, I.; Markulak, D. Applications of aluminium alloys in civil engineering. *Tehnički Vjesnik* **2017**, *24*, 1609–1618.
38. Hihara, L. Corrosion of metal matrix composites. Reference module in materials science and materials engineering. *Shreir's Corros.* **2010**, *3*, 2250–2269.
39. Alves, F.L.; Baptista, A.; Marques, A. Metal and ceramic matrix composites in aerospace engineering. In *Advanced Composite Materials for Aerospace Engineering*; Elsevier: Duxford, UK, 2016; pp. 59–99.
40. Miracle, D.B. Opportunities and approaches for doubling the structural efficiency of metallic materials. In *Metallic Materials with High Structural Efficiency*; Springer: Berlin/Heidelberg, Germany, 2004; pp. 3–20.
41. Mouritz, A.P.; Gellert, E.; Burchill, P.; Challis, K. Review of advanced composite structures for naval ships and submarines. *Compos. Struct.* **2001**, *53*, 21–42. [CrossRef]
42. Babalola, P.; Bolu, C.; Inegbenebor, A.; Odunfa, K. Development of aluminium matrix composites: A review. *Online Int. J. Eng. Technol. Res.* **2014**, *2*, 1–11.
43. Surappa, M. Aluminium matrix composites: Challenges and opportunities. *Sadhana* **2003**, *28*, 319–334. [CrossRef]

44. Garg, P.; Jamwal, A.; Kumar, D.; Sadasivuni, K.K.; Hussain, C.M.; Gupta, P. Advance research progresses in aluminium matrix composites: Manufacturing & applications. *J. Mater. Res. Technol.* **2019**, *8*, 4924–4939.
45. Karvanis, K.; Fasnakis, D.; Maropoulos, A.; Papanikolaou, S. Production and mechanical properties of Al-SiC metal matrix composites. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Kozani, Greece, 23–25 September 2016; p. 012070.
46. Shaikh, M.B.N.; Aziz, T.; Arif, S.; Ansari, A.H.; Karagiannidis, P.G.; Uddin, M. Effect of sintering techniques on microstructural, mechanical and tribological properties of Al-SiC composites. *Surf. Interfaces* **2020**, *20*, 100598. [CrossRef]
47. Xiao, C.; Chen, L.; Tang, Y.; Zhang, X.; Zheng, K.; Tian, X. Three dimensional porous alumina network for polymer composites with enhanced thermal conductivity. *Compos. Part A Appl. Sci. Manuf.* **2019**, *124*, 105511. [CrossRef]
48. Ben-Nissan, B.; Choi, A.; Cordingley, R. Alumina ceramics. In *Bioceramics and Their Clinical Applications*; Elsevier: Cambridge, UK, 2008; pp. 223–242.
49. Rahimian, M.; Ehsani, N.; Parvin, N.; reza Baharvandi, H. The effect of particle size, sintering temperature and sintering time on the properties of Al–Al_2O_3 composites, made by powder metallurgy. *J. Mater. Processing Technol.* **2009**, *209*, 5387–5393. [CrossRef]
50. Gudlur, P.; Forness, A.; Lentz, J.; Radovic, M.; Muliana, A. Thermal and mechanical properties of Al/Al_2O_3 composites at elevated temperatures. *Mater. Sci. Eng. A* **2012**, *531*, 18–27. [CrossRef]
51. Rahimian, M.; Ehsani, N.; Parvin, N.; Baharvandi, H. The effect of sintering temperature and the amount of reinforcement on the properties of Al–Al_2O_3 composite. *Mater. Des.* **2009**, *30*, 3333–3337. [CrossRef]
52. Garbiec, D.; Jurczyk, M.; Levintant-Zayonts, N.; Mościcki, T. Properties of Al–Al_2O_3 composites synthesized by spark plasma sintering method. *Arch. Civ. Mech. Eng.* **2015**, *15*, 933–939. [CrossRef]
53. Nourouzi, S.; Damavandi, E.; Rabiee, S.M. Microstructural and mechanical properties of Al-Al_2O_3 composites focus on experimental techniques. *Int. J. Microstruct. Mater. Prop.* **2016**, *11*, 383–398.
54. Park, B.; Crosky, A.; Hellier, A. Fracture toughness of microsphere Al_2O_3–Al particulate metal matrix composites. *Compos. Part B Eng.* **2008**, *39*, 1270–1279. [CrossRef]
55. Kok, M. Production and mechanical properties of Al_2O_3 particle-reinforced 2024 aluminium alloy composites. *J. Mater. Processing Technol.* **2005**, *161*, 381–387. [CrossRef]
56. Kumar, A.; Lal, S.; Kumar, S. Fabrication and characterization of A359/Al_2O_3 metal matrix composite using electromagnetic stir casting method. *J. Mater. Res. Technol.* **2013**, *2*, 250–254. [CrossRef]
57. Qiu, J.Y.; Watari, K.; Hotta, Y.; Mitsuishi, K. Influence of powder characteristics on sintering of AlN ceramics. *Key Eng. Mater.* **2007**, *280*, 1409–1412. [CrossRef]
58. Zhou, Y.; Hu, J.; Chen, X.; Yu, F.; He, J. Thermoplastic polypropylene/aluminum nitride nanocomposites with enhanced thermal conductivity and low dielectric loss. *IEEE Trans. Dielectr. Electr. Insul.* **2016**, *23*, 2768–2776. [CrossRef]
59. Abdoli, H.; Saebnouri, E.; Sadrnezhaad, S.K.; Ghanbari, M.; Shahrabi, T. Processing and surface properties of Al–AlN composites produced from nanostructured milled powders. *J. Alloys Compd.* **2010**, *490*, 624–630. [CrossRef]
60. Mizuuchi, K.; Inoue, K.; Agari, Y.; Nagaoka, T.; Sugioka, M.; Tanaka, M.; Takeuchi, T.; Tani, J.-i.; Kawahara, M.; Makino, Y. Processing and thermal properties of Al/AlN composites in continuous solid–liquid co-existent state by spark plasma sintering. *Compos. Part B Eng.* **2012**, *43*, 1557–1563. [CrossRef]
61. Yu, P.; Balog, M.; Yan, M.; Schaffer, G.; Qian, M. In situ fabrication and mechanical properties of Al–AlN composite by hot extrusion of partially nitrided AA6061 powder. *J. Mater. Res.* **2011**, *26*, 1719–1725. [CrossRef]
62. Pradhan, S.; Jena, S.; Patnaik, S.; Swain, P.; Majhi, J. Wear characteristics of Al-AlN composites produced in-situ by nitrogenation. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Rourkela, India, 5–6 December 2014; p. 012034.
63. Balog, M.; Krizik, P.; Dvorak, J.; Bajana, O.; Krajcovic, J.; Drienovsky, M. Industrially fabricated in-situ Al-AlN metal matrix composites (part B): The mechanical, creep, and thermal properties. *J. Alloys Compd.* **2022**, *909*, 164720. [CrossRef]
64. Mohanavel, V.; Ravichandran, M. Experimental investigation on mechanical properties of AA7075-AlN composites. *Mater. Test.* **2019**, *61*, 554–558. [CrossRef]
65. Grech, J.; Antunes, E. Zirconia in dental prosthetics: A literature review. *J. Mater. Res. Technol.* **2019**, *8*, 4956–4964. [CrossRef]
66. Turon-Vinas, M.; Anglada, M. Strength and fracture toughness of zirconia dental ceramics. *Dent. Mater.* **2018**, *34*, 365–375. [CrossRef]
67. Haddadi, S.; Mahdavian, M.; Karimi, E. Evaluation of the corrosion protection properties of an epoxy coating containing sol–gel surface modified nano-zirconia on mild steel. *RSC Adv.* **2015**, *5*, 28769–28777. [CrossRef]
68. Volpato, C.Â.M.; Garbelotto, L.; Fredel, M.C.; Bondioli, F. Application of zirconia in dentistry: Biological, mechanical and optical considerations. *Adv. Ceram.-Electr. Magn. Ceram. Bioceram. Ceram. Environ.* **2011**, *25*, 397–420.
69. Walker, R.C.; Potochniak, A.E.; Hyer, A.P.; Ferri, J.K. Zirconia aerogels for thermal management: Review of synthesis, processing, and properties information architecture. *Adv. Colloid Interface Sci.* **2021**, *295*, 102464. [CrossRef]
70. Pal, K.; Navin, K.; Kurchania, R. Study of structural and mechanical behaviour of Al-ZrO_2 metal matrix nanocomposites prepared by powder metallurgy method. *Mater. Today: Proc.* **2020**, *26*, 2714–2719. [CrossRef]
71. Mazaheri, Y.; Jalilvand, M.M.; Heidarpour, A.; Jahani, A.R. Tribological behavior of AZ31/ZrO_2 surface nanocomposites developed by friction stir processing. *Tribol. Int.* **2020**, *143*, 106062. [CrossRef]
72. Kumar, G.V.; Pramod, R.; Sekhar, C.G.; Kumar, G.P.; Bhanumurthy, T. Investigation of physical, mechanical and tribological properties of Al6061–ZrO_2 nano-composites. *Heliyon* **2019**, *5*, e02858. [CrossRef] [PubMed]

73. Baghchesara, M.; Baharvandi, H.; Abdizadeh, H. Investigation on mechanical properties and surfaces fracture of Al/ZrO_2 composite. In Proceedings of the International Conference on Smart Materials and Nanotechnology in Engineering, Harbin, China, 1–4 July 2007; pp. 1554–1559.
74. James, S.J.; Ganesan, M.; Santhamoorthy, P.; Kuppan, P. Development of hybrid aluminium metal matrix composite and study of property. *Mater. Today Proc.* **2018**, *5*, 13048–13054. [CrossRef]
75. Abdizadeh, H.; Baghchesara, M.A. Investigation on mechanical properties and fracture behavior of A356 aluminum alloy based ZrO_2 particle reinforced metal-matrix composites. *Ceram. Int.* **2013**, *39*, 2045–2050. [CrossRef]
76. Rajabi, M.; Khodai, M.; Askari, N. Microwave-assisted sintering of Al–ZrO_2 nano-composites. *J. Mater. Sci. Mater. Electron.* **2014**, *25*, 4577–4584. [CrossRef]
77. Yadav, M.; Kumaraswamidhas, L.; Singh, S.K. Investigation of solid particle erosion behavior of Al-Al_2O_3 and Al-ZrO_2 metal matrix composites fabricated through powder metallurgy technique. *Tribol. Int.* **2022**, *172*, 107636. [CrossRef]
78. Mazahery, A.; Shabani, M.O. Microstructural and abrasive wear properties of SiC reinforced aluminum-based composite produced by compocasting. *Trans. Nonferrous Met. Soc. China* **2013**, *23*, 1905–1914. [CrossRef]
79. Zhou, K.; Xiao, G.; Xu, J.; Huang, Y. Material removal behavior of Cf/SiC ceramic matrix composites as a function of abrasive wear during diamond abrasive belt grinding. *Wear* **2021**, *486*, 204101. [CrossRef]
80. Zhang, L.; Xu, H.; Wang, Z.; Li, Q.; Wu, J. Mechanical properties and corrosion behavior of Al/SiC composites. *J. Alloys Compd.* **2016**, *678*, 23–30. [CrossRef]
81. Patel, M.; Sahu, S.K.; Singh, M.K. Abrasive wear behavior of SiC particulate reinforced AA5052 metal matrix composite. *Mater. Today Proc.* **2020**, *33*, 5586–5591. [CrossRef]
82. Kumar, M.S.; Begum, S.R.; Pruncu, C.; Asl, M.S. Role of homogeneous distribution of SiC reinforcement on the characteristics of stir casted Al–SiC composites. *J. Alloys Compd.* **2021**, *869*, 159250. [CrossRef]
83. Soltani, S.; Azari Khosroshahi, R.; Taherzadeh Mousavian, R.; Jiang, Z.-Y.; Fadavi Boostani, A.; Brabazon, D. Stir casting process for manufacture of Al–SiC composites. *Rare Met.* **2017**, *36*, 581–590. [CrossRef]
84. Moses, J.J.; Dinaharan, I.; Sekhar, S.J. Characterization of silicon carbide particulate reinforced AA6061 aluminum alloy composites produced via stir casting. *Procedia Mater. Sci.* **2014**, *5*, 106–112. [CrossRef]
85. Nirala, A.; Soren, S.; Kumar, N.; Dwivedi, V.; Kaushal, D. A comprehensive review on stir cast Al-SiC composite. *Mater. Today Proc.* **2020**, *21*, 1610–1614. [CrossRef]
86. Zakaria, H. Microstructural and corrosion behavior of Al/SiC metal matrix composites. *Ain Shams Eng. J.* **2014**, *5*, 831–838. [CrossRef]
87. Mosleh-Shirazi, S.; Akhlaghi, F.; Li, D.-Y. Effect of SiC content on dry sliding wear, corrosion and corrosive wear of Al/SiC nanocomposites. *Trans. Nonferrous Met. Soc. China* **2016**, *26*, 1801–1808. [CrossRef]
88. Kitayama, M.; Hirao, K.; Toriyama, M.; Kanzaki, S. High hardness α-Si_3N_4 ceramics reinforced by rod-like β-Si_3N_4 seed particles. *J. Ceram. Soc. Jpn.* **2000**, *108*, 646–649. [CrossRef]
89. Okada, A. Automotive and industrial applications of structural ceramics in Japan. *J. Eur. Ceram. Soc.* **2008**, *28*, 1097–1104. [CrossRef]
90. Hoffmann, M. High-temperature properties of Si_3N_4 ceramics. *MRS Bull.* **1995**, *20*, 28–32. [CrossRef]
91. Ul Haq, M.I.; Anand, A. Dry sliding friction and wear behavior of AA7075-Si_3N_4 composite. *Silicon* **2018**, *10*, 1819–1829. [CrossRef]
92. Mattli, M.R.; Matli, P.R.; Shakoor, A.; Amer Mohamed, A.M. Structural and mechanical properties of amorphous Si_3N_4 nanoparticles reinforced Al matrix composites prepared by microwave sintering. *Ceramics* **2019**, *2*, 126–134. [CrossRef]
93. Mohanavel, V.; Ali, K.A.; Prasath, S.; Sathish, T.; Ravichandran, M. Microstructural and tribological characteristics of AA6351/Si_3N_4 composites manufactured by stir casting. *J. Mater. Res. Technol.* **2020**, *9*, 14662–14672. [CrossRef]
94. Ertug, B. *Sintering Applications*; BoD–Books on Demand: Norderstedt, Germany, 2013.
95. Firestein, K.L.; Steinman, A.E.; Golovin, I.S.; Cifre, J.; Obraztsova, E.A.; Matveev, A.T.; Kovalskii, A.M.; Lebedev, O.I.; Shtansky, D.V.; Golberg, D. Fabrication, characterization, and mechanical properties of spark plasma sintered Al–BN nanoparticle composites. *Mater. Sci. Eng. A* **2015**, *642*, 104–112. [CrossRef]
96. Gostariani, R.; Ebrahimi, R.; Asadabad, M.A.; Paydar, M.H. Mechanical properties of Al/BN nanocomposites fabricated by planetary ball milling and conventional hot extrusion. *Acta Metall. Sin. Engl. Lett.* **2018**, *31*, 245–253. [CrossRef]
97. Xue, Y.; Jiang, B.; Bourgeois, L.; Dai, P.; Mitome, M.; Zhang, C.; Yamaguchi, M.; Matveev, A.; Tang, C.; Bando, Y. Aluminum matrix composites reinforced with multi-walled boron nitride nanotubes fabricated by a high-pressure torsion technique. *Mater. Des.* **2015**, *88*, 451–460. [CrossRef]
98. Firestein, K.; Corthay, S.; Steinman, A.; Matveev, A.; Kovalskii, A.; Sukhorukova, I.; Golberg, D.; Shtansky, D. High-strength aluminum-based composites reinforced with BN, AlB2 and AlN particles fabricated via reactive spark plasma sintering of Al-BN powder mixtures. *Mater. Sci. Eng. A* **2017**, *681*, 1–9. [CrossRef]
99. Reddy, M.P.; Manakari, V.; Parande, G.; Ubaid, F.; Shakoor, R.; Mohamed, A.; Gupta, M. Enhancing compressive, tensile, thermal and damping response of pure Al using BN nanoparticles. *J. Alloys Compd.* **2018**, *762*, 398–408. [CrossRef]
100. Arlic, U.; Drozd, Z.; Trojanová, Z.; Molnárová, O.; Kasakewitsch, A. Characterisation of an Al-BN nanocomposite prepared by ball milling and hot extrusion. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Risø, Denmark, 4–8 September 2017; p. 012011.

101. Domnich, V.; Reynaud, S.; Haber, R.A.; Chhowalla, M. Boron carbide: Structure, properties, and stability under stress. *J. Am. Ceram. Soc.* **2011**, *94*, 3605–3628. [CrossRef]
102. Liu, C. Structure and properties of boron carbide with aluminum incorporation. *Mater. Sci. Eng. B* **2000**, *72*, 23–26. [CrossRef]
103. Jianxin, D. Erosion wear of boron carbide ceramic nozzles by abrasive air-jets. *Mater. Sci. Eng. A* **2005**, *408*, 227–233. [CrossRef]
104. Ibrahim, M.; Ammar, H.; Samuel, A.; Soliman, M.; Almajid, A.; Samuel, F. Mechanical properties and fracture of Al–15 vol.-% B4C based metal matrix composites. *Int. J. Cast Met. Res.* **2014**, *27*, 7–14. [CrossRef]
105. Shorowordi, K.M.; Haseeb, A.; Celis, J.P. Tribo-surface characteristics of Al–B4C and Al–SiC composites worn under different contact pressures. *Wear* **2006**, *261*, 634–641. [CrossRef]
106. Wu, C.; Fang, P.; Luo, G.; Chen, F.; Shen, Q.; Zhang, L.; Lavernia, E.J. Effect of plasma activated sintering parameters on microstructure and mechanical properties of Al-7075/B4C composites. *J. Alloys Compd.* **2014**, *615*, 276–282. [CrossRef]
107. Auradi, V.; Rajesh, G.; Kori, S. Processing of B4C Particulate Reinforced 6061Aluminum Matrix Composites by melt stirring involving two-step addition. *Procedia Mater. Sci.* **2014**, *6*, 1068–1076. [CrossRef]
108. Canakci, A.; Varol, T.; Özkaya, S.; Erdemir, F. Microstructure and properties of Al-B4C functionally graded materials produced by powder metallurgy method. *Univers. J. Mater. Sci.* **2014**, *2*, 90–95. [CrossRef]
109. Isfahani, M.J.N.; Payami, F.; Asadabad, M.A.; Shokri, A.A. Investigation of the effect of boron carbide nanoparticles on the structural, electrical and mechanical properties of Al-B4C nanocomposites. *J. Alloys Compd.* **2019**, *797*, 1348–1358. [CrossRef]
110. Iijima, S. Helical microtubules of graphitic carbon. *Nature* **1991**, *354*, 56–58. [CrossRef]
111. Iijima, S. Carbon nanotubes. *MRS Bull.* **1994**, *19*, 43–49. [CrossRef]
112. Bethune, D.; Kiang, C.H.; De Vries, M.; Gorman, G.; Savoy, R.; Vazquez, J.; Beyers, R. Cobalt-catalysed growth of carbon nanotubes with single-atomic-layer walls. *Nature* **1993**, *363*, 605–607. [CrossRef]
113. Treacy, M.J.; Ebbesen, T.; Gibson, J. Exceptionally high Young's modulus observed for individual carbon nanotubes. *Nature* **1996**, *381*, 678–680. [CrossRef]
114. Obitayo, W.; Liu, T. A review: Carbon nanotube-based piezoresistive strain sensors. *J. Sens.* **2012**, *2012*, 652438. [CrossRef]
115. Liu, X.; Lee, C.; Zhou, C.; Han, J. Carbon nanotube field-effect inverters. *Appl. Phys. Lett.* **2001**, *79*, 3329–3331. [CrossRef]
116. Chu, L.L.; Que, L.; Gianchandani, Y.B. Measurements of material properties using differential capacitive strain sensors. *J. Microelectromech. Syst.* **2002**, *11*, 489–498. [CrossRef]
117. Yildirim, M.; Özyürek, D.; Gürü, M. Investigation of microstructure and wear behaviors of al matrix composites reinforced by carbon nanotube. *Fuller. Nanotub. Carbon Nanostruct.* **2016**, *24*, 467–473. [CrossRef]
118. Kumar, L.; Nasimul Alam, S.; Sahoo, S.K. Mechanical properties, wear behavior and crystallographic texture of Al–multiwalled carbon nanotube composites developed by powder metallurgy route. *J. Compos. Mater.* **2017**, *51*, 1099–1117. [CrossRef]
119. Chen, B.; Li, S.; Imai, H.; Jia, L.; Umeda, J.; Takahashi, M.; Kondoh, K. Carbon nanotube induced microstructural characteristics in powder metallurgy Al matrix composites and their effects on mechanical and conductive properties. *J. Alloys Compd.* **2015**, *651*, 608–615. [CrossRef]
120. Lu, Q.; Ni, S.; Guo, B.; Gu, J.; Adeli, M.; Song, M. Effects of the addition of CNTs and Al alloying on the microstructure and properties of Cu-(Al)/CNTs composites. *Diam. Relat. Mater.* **2021**, *120*, 108600. [CrossRef]
121. Sahoo, B.; Joseph, J.; Sharma, A.; Paul, J. Particle size and shape effects on the surface mechanical properties of aluminium coated with carbonaceous materials. *J. Compos. Mater.* **2019**, *53*, 261–270. [CrossRef]
122. Park, J.G.; Keum, D.H.; Lee, Y.H. Strengthening mechanisms in carbon nanotube-reinforced aluminum composites. *Carbon* **2015**, *95*, 690–698. [CrossRef]
123. George, R.; Kashyap, K.; Rahul, R.; Yamdagni, S. Strengthening in carbon nanotube/aluminium (CNT/Al) composites. *Scr. Mater.* **2005**, *53*, 1159–1163. [CrossRef]
124. Yu, M.-F.; Lourie, O.; Dyer, M.J.; Moloni, K.; Kelly, T.F.; Ruoff, R.S. Strength and breaking mechanism of multiwalled carbon nanotubes under tensile load. *Science* **2000**, *287*, 637–640. [CrossRef]
125. Esteve, J.; Zambrano, G.; Rincon, C.; Martinez, E.; Galindo, H.; Prieto, P. Mechanical and tribological properties of tungsten carbide sputtered coatings. *Thin Solid Film.* **2000**, *373*, 282–286. [CrossRef]
126. Krishna, A.R.; Arun, A.; Unnikrishnan, D.; Shankar, K.V. An investigation on the mechanical and tribological properties of alloy A356 on the addition of WC. *Mater. Today Proc.* **2018**, *5*, 12349–12355. [CrossRef]
127. Megahed, A.; Mohamed, M.A.; Abdel Hamid, M.; Zoalfakar, S.H. Microstructure, hardness, and wear properties of AA6061/WC nanocomposite fabricated by friction stir processing. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2022**, *236*, 09544062221091904. [CrossRef]
128. Raviraj, M.; Sharanprabhu, C.; Mohankumar, G. Experimental analysis on processing and properties of Al-TiC metal matrix composites. *Procedia Mater. Sci.* **2014**, *5*, 2032–2038. [CrossRef]
129. Bauri, R.; Yadav, D.; Suhas, G. Effect of friction stir processing (FSP) on microstructure and properties of Al–TiC in situ composite. *Mater. Sci. Eng. A* **2011**, *528*, 4732–4739. [CrossRef]
130. Agrawal, E.; Tungikar, V. Study on tribological properties of Al-TiC composites by Taguchi method. *Mater. Today Proc.* **2020**, *26*, 2242–2247. [CrossRef]
131. Wang, Z.; Qiu, Z.; Sun, H.; Liu, W. Effect of TiC content on the microstructure, texture and mechanical properties of 1060/Al–TiC/1060 laminated composites. *J. Alloys Compd.* **2019**, *806*, 788–797. [CrossRef]

132. Parswajinan, C.; Ramnath, B.V.; Abishek, S.; Niharishsagar, B.; Sridhar, G. Hardness and impact behaviour of aluminium metal matrix composite. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Tamilnadu, India, 8–9 March 2018; p. 012075.
133. Chamis, C.; Lark, R. Hybrid composites-State-of-the-art review: Analysis, design, application and fabrication. In Proceedings of the 18th Structural Dynamics and Materials Conference, San Diego, CA, USA, 21–23 March 1977; p. 415.
134. Banerjee, S.; Sankar, B.V. Mechanical properties of hybrid composites using finite element method based micromechanics. *Compos. Part B Eng.* **2014**, *58*, 318–327. [CrossRef]
135. Akinwamide, S.O.; Akinribide, O.J.; Olubambi, P.A. Microstructural evolution, mechanical and nanoindentation studies of stir cast binary and ternary aluminium based composites. *J. Alloys Compd.* **2021**, *850*, 156586. [CrossRef]
136. Baradeswaran, A.; Vettivel, S.; Perumal, A.E.; Selvakumar, N.; Issac, R.F. Experimental investigation on mechanical behaviour, modelling and optimization of wear parameters of B4C and graphite reinforced aluminium hybrid composites. *Mater. Des.* **2014**, *63*, 620–632. [CrossRef]
137. Radhika, N.; Subramanian, R. Effect of reinforcement on wear behaviour of aluminium hybrid composites. *Tribol.-Mater. Surf. Interfaces* **2013**, *7*, 36–41. [CrossRef]
138. Kumar, N.S.; Ravindranath, V.; Shankar, G.S. Mechanical and wear behaviour of aluminium metal matrix hybrid composites. *Procedia Mater. Sci.* **2014**, *5*, 908–917. [CrossRef]
139. Prakash, C.; Singh, S.; Sharma, S.; Garg, H.; Singh, J.; Kumar, H.; Singh, G. Fabrication of aluminium carbon nano tube silicon carbide particles based hybrid nano-composite by spark plasma sintering. *Mater. Today Proc.* **2020**, *21*, 1637–1642. [CrossRef]
140. Ghasali, E.; Pakseresht, A.; Rahbari, A.; Eslami-Shahed, H.; Alizadeh, M.; Ebadzadeh, T. Mechanical properties and microstructure characterization of spark plasma and conventional sintering of Al–SiC–TiC composites. *J. Alloys Compd.* **2016**, *666*, 366–371. [CrossRef]
141. Oladijo, O.; Popoola, A.; Ujah, C.; Namoshe, M. Dataset of spark plasma sintering of AlZnSn alloy for soft solder application. *Data Brief* **2019**, *24*, 103948. [CrossRef] [PubMed]
142. Venkatesh, V.; Deoghare, A.B. Effect of Sintering Mechanisms on the Mechanical Behaviour of SiC and Kaoline Reinforced Hybrid Aluminium Metal Matrix Composite Fabricated through Powder Metallurgy Technique. *Silicon* **2022**, *14*, 5481–5493. [CrossRef]
143. Shaikh, M.B.N.; Arif, S.; Siddiqui, M.A. Fabrication and characterization of aluminium hybrid composites reinforced with fly ash and silicon carbide through powder metallurgy. *Mater. Res. Express* **2018**, *5*, 046506. [CrossRef]
144. Tan, A.; Teng, J.; Zeng, X.; Fu, D.; Zhang, H. Fabrication of aluminium matrix hybrid composites reinforced with SiC microparticles and TiB2 nanoparticles by powder metallurgy. *Powder Metall.* **2017**, *60*, 66–72. [CrossRef]
145. Pugalenthi, P. Study of the microstructures and mechanical properties of aluminium hybrid composites with. *Mater. Tehnol.* **2019**, *53*, 49–55. [CrossRef]
146. Mohanavel, V.; Rajan, K.; Senthil, P.; Arul, S. Mechanical behaviour of hybrid composite (AA6351+ Al_2O_3+ Gr) fabricated by stir casting method. *Mater. Today Proc.* **2017**, *4*, 3093–3101. [CrossRef]
147. Arif, S.; Alam, M.T.; Ansari, A.H.; Siddiqui, M.A.; Mohsin, M. Study of mechanical and tribological behaviour of Al/SiC/ZrO_2 hybrid composites fabricated through powder metallurgy technique. *Mater. Res. Express* **2017**, *4*, 076511. [CrossRef]
148. Manikandan, R.; Arjunan, T. Mechanical and tribological behaviours of aluminium hybrid composites reinforced by CDA-B4C. *Mater. Res. Express* **2020**, *7*, 016584. [CrossRef]
149. Venkatesh, L.; Arjunan, T.; Ravikumar, K. Microstructural characteristics and mechanical behaviour of aluminium hybrid composites reinforced with groundnut shell ash and B4C. *J. Braz. Soc. Mech. Sci. Eng.* **2019**, *41*, 295. [CrossRef]
150. Kumar, R.A.; Devaraju, A.; Arunkumar, S. Experimental investigation on mechanical behaviour and wear parameters of tic and graphite reinforced aluminium hybrid composites. *Mater. Today Proc.* **2018**, *5*, 14244–14251. [CrossRef]
151. Wu, Q.; Xu, Y.; Yao, Z.; Liu, A.; Shi, G. Supercapacitors based on flexible graphene/polyaniline nanofiber composite films. *ACS Nano* **2010**, *4*, 1963–1970. [CrossRef] [PubMed]
152. Raja, S.; Muhamad, M.R.; Jamaludin, M.F.; Yusof, F. A review on nanomaterials reinforcement in friction stir welding. *J. Mater. Res. Technol.* **2020**, *9*, 16459–16487. [CrossRef]
153. Abdo, H.S.; Mohammed, M.L.; Khalil, K.A. Fiber-reinforced metal-matrix composites. In *Fiber Reinforced Composites*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 649–667.
154. Chen, L.; Qi, Y.; Fei, Y.; Du, Z. Enhanced mechanical properties and thermal conductivity for GNPs/Al2024 composites with in situ SiC nanorods. *Met. Mater. Int.* **2021**, *27*, 4263–4270. [CrossRef]
155. Bodunrin, M.O.; Alaneme, K.K.; Chown, L.H. Aluminium matrix hybrid composites: A review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. *J. Mater. Res. Technol.* **2015**, *4*, 434–445. [CrossRef]
156. Miracle, D. Metal matrix composites–from science to technological significance. *Compos. Sci. Technol.* **2005**, *65*, 2526–2540. [CrossRef]
157. Rajmohan, T.; Palanikumar, K.; Arumugam, S. Synthesis and characterization of sintered hybrid aluminium matrix composites reinforced with nanocopper oxide particles and microsilicon carbide particles. *Compos. Part B Eng.* **2014**, *59*, 43–49. [CrossRef]
158. Saheb, N.; Iqbal, Z.; Khalil, A.; Hakeem, A.S.; Al Aqeeli, N.; Laoui, T.; Al-Qutub, A.; Kirchner, R. Spark plasma sintering of metals and metal matrix nanocomposites: A review. *J. Nanomater.* **2012**, *2012*, 983470. [CrossRef]

159. Ruiz-Esparza-Rodríguez, M.; Garay-Reyes, C.; Mendoza-Duarte, J.; Estrada-Guel, I.; Hernández-Rivera, J.; Cruz-Rivera, J.; Gutiérrez-Castañeda, E.; González, S.; Garay-Tapia, A.; Martínez-Sánchez, R. Evaluation of high-frequency induction heat sintering and conventional sintering in AlxCoCrFeMnNi high-entropy alloys. *J. Alloys Compd.* **2022**, *910*, 164780. [CrossRef]
160. Mendoza-Duarte, J.; Robles-Hernandez, F.; Estrada-Guel, I.; Martínez-Sánchez, R. Aluminum sintering in air atmosphere using high frequency induction heating. *Microsc. Microanal.* **2017**, *23*, 1950–1951. [CrossRef]
161. Khalil, K.A.; Sherif, E.-S.M.; Nabawy, A.; Abdo, H.S.; Marzouk, W.W.; Alharbi, H.F. Titanium carbide nanofibers-reinforced aluminum compacts, a new strategy to enhance mechanical properties. *Materials* **2016**, *9*, 399. [CrossRef]
162. Oliver, U.C.; Sunday, A.V.; Christain, E.I.-E.I.; Elizabeth, M.M. Spark plasma sintering of aluminium composites—A review. *Int. J. Adv. Manuf. Technol.* **2021**, *112*, 1819–1839. [CrossRef]
163. Li, J.F.; Wang, K.; Zhang, B.P.; Zhang, L.M. Ferroelectric and piezoelectric properties of fine-grained Na0. 5K0. 5NbO3 lead-free piezoelectric ceramics prepared by spark plasma sintering. *J. Am. Ceram. Soc.* **2006**, *89*, 706–709. [CrossRef]
164. Heng, W.; Jingfeng, L.; Cewen, N.; Min, Z.; Weishu, L.; Boping, Z.; Kita, T. High-performance Ag0.8 Pb18+x SbTe20 thermoelectric bulk materials fabricated by mechanical alloying and spark plasma sintering. *Appl. Phys. Lett.* **2006**, *88*, 092104.
165. Ujah, C.; Popoola, A.; Popoola, O.; Aigbodion, V. Enhanced tribology, thermal and electrical properties of Al-CNT composite processed via spark plasma sintering for transmission conductor. *J. Mater. Sci.* **2019**, *54*, 14064–14073. [CrossRef]
166. Beheshtipour, A.; Mahdizadeh, S.M.; Khademi, D.; Khodeir, E.; Emamiyan, H. Comparison of Mechanical Properties and Corrosion Behavior of Al-NanoAl_2O_3 with Al-MicroAl_2O_3 Composites Made by SPS Process. *Met. Mater. Int.* **2020**, *26*, 1697–1709. [CrossRef]
167. Chai, J.; Zhu, Y.; Wang, Z.; Shen, T.; Liu, Y.; Niu, L.; Li, S.; Yao, C.; Cui, M.; Liu, C. Microstructure and mechanical properties of SPS sintered Al_2O_3–ZrO_2 (3Y)–SiC ceramic composites. *Mater. Sci. Eng. A* **2020**, *781*, 139197. [CrossRef]
168. Ujah, C.; Popoola, A.; Popoola, O.; Afolabi, A.; Uyor, U. Mechanical and Oxidation Characteristics of Ti20-Al16-V16-Fe16-Ni16-Cr16 High-Entropy Alloy Developed via Spark Plasma Sintering for High-Temperature/Strength Applications. *J. Mater. Eng. Perform.* **2022**, 1–11. [CrossRef]
169. Fattahi, M.; Mohammadzadeh, A.; Pazhouhanfar, Y.; Shaddel, S.; Asl, M.S.; Namini, A.S. Influence of SPS temperature on the properties of TiC–SiCw composites. *Ceram. Int.* **2020**, *46*, 11735–11742. [CrossRef]
170. Moazzen, P.; Toroghinejad, M.R.; Karimzadeh, F.; Vleugels, J.; Ravash, H.; Cavaliere, P. Influence of zirconium addition on the microstructure, thermodynamic stability, thermal stability and mechanical properties of mechanical alloyed spark plasma sintered (MA-SPS) FeCoCrNi high entropy alloy. *Powder Metall.* **2018**, *61*, 405–416. [CrossRef]
171. Thomson, K.; Jiang, D.; Yao, W.; Ritchie, R.; Mukherjee, A. Characterization and mechanical testing of alumina-based nanocomposites reinforced with niobium and/or carbon nanotubes fabricated by spark plasma sintering. *Acta Mater.* **2012**, *60*, 622–632. [CrossRef]
172. Rohatgi, P. Cast aluminum-matrix composites for automotive applications. *Jom* **1991**, *43*, 10–15. [CrossRef]
173. Ravi, K.; Sreekumar, V.; Pillai, R.; Mahato, C.; Amaranathan, K.; Pai, B. Optimization of mixing parameters through a water model for metal matrix composites synthesis. *Mater. Des.* **2007**, *28*, 871–881. [CrossRef]
174. Singla, M.; Dwivedi, D.D.; Singh, L.; Chawla, V. Development of aluminium based silicon carbide particulate metal matrix composite. *J. Miner. Mater. Charact. Eng.* **2009**, *8*, 455–467. [CrossRef]
175. Hashim, J. The production of cast metal matrix composite by a modified stir casting method. *J. Teknol.* **2001**, *35*, 9–20. [CrossRef]
176. Rajan, T.; Pillai, R.; Pai, B. Reinforcement coatings and interfaces in aluminium metal matrix composites. *J. Mater. Sci.* **1998**, *33*, 3491–3503. [CrossRef]
177. Kalaiselvan, K.; Murugan, N.; Parameswaran, S. Production and characterization of AA6061–B4C stir cast composite. *Mater. Des.* **2011**, *32*, 4004–4009. [CrossRef]
178. Pai, B.; Ramani, G.; Pillai, R.; Satyanarayana, K. Role of magnesium in cast aluminium alloy matrix composites. *J. Mater. Sci.* **1995**, *30*, 1903–1911. [CrossRef]
179. Shorowordi, K.M.; Laoui, T.; Haseeb, A.A.; Celis, J.-P.; Froyen, L. Microstructure and interface characteristics of B4C, SiC and Al_2O_3 reinforced Al matrix composites: A comparative study. *J. Mater. Processing Technol.* **2003**, *142*, 738–743. [CrossRef]
180. Zulfia, A.; Atkinson, H.; Jones, H.; King, S. Effect of hot isostatic pressing on cast A357 aluminium alloy with and without SiC particle reinforcement. *J. Mater. Sci.* **1999**, *34*, 4305–4310. [CrossRef]
181. Akinlabi, E.T.; Mahamood, R.; Akinlabi, S.; Ogunmuyiwa, E. Processing parameters influence on wear resistance behaviour of friction stir processed Al-TiC composites. *Adv. Mater. Sci. Eng.* **2014**, *2014*, 724590. [CrossRef]
182. Prakrathi, S.; Ravikumar, M.; Udupa, K.; Udaya Bhat, K. Fabrication of hybrid surface composite through friction stir processing and its impression creep behaviour. *Int. Sch. Res. Not.* **2013**, *2013*, 541762. [CrossRef]
183. Izadi, H.; Nolting, A.; Munro, C.; Bishop, D.; Plucknett, K.; Gerlich, A. Friction stir processing of Al/SiC composites fabricated by powder metallurgy. *J. Mater. Processing Technol.* **2013**, *213*, 1900–1907. [CrossRef]
184. Zahmatkesh, B.; Enayati, M. A novel approach for development of surface nanocomposite by friction stir processing. *Mater. Sci. Eng. A* **2010**, *527*, 6734–6740. [CrossRef]
185. Ozturk, K.; Gecu, R.; Karaaslan, A. Microstructure, wear and corrosion characteristics of multiple-reinforced (SiC–B4C–Al_2O_3) Al matrix composites produced by liquid metal infiltration. *Ceram. Int.* **2021**, *47*, 18274–18285. [CrossRef]
186. Kisasoz, A.; Guler, K.A.; Karaaslan, A. Infiltration of A6063 aluminium alloy into SiC–B4C hybrid preforms using vacuum assisted block mould investment casting technique. *Trans. Nonferrous Met. Soc. China* **2012**, *22*, 1563–1567. [CrossRef]

187. Ujah, C.O.; Kallon, D.V.V.; Aikhuele, D.O.; Aigbodion, V.S. Advanced Composite Materials: A Panacea for Improved Electricity Transmission. *Appl. Sci.* **2022**, *12*, 8291. [CrossRef]
188. Caceres, C.H. Economical and environmental factors in light alloys automotive applications. *Metall. Mater. Trans. A* **2007**, *38*, 1649–1662. [CrossRef]
189. Withers, G.; De Waas Tilakaratna, P. Performance evaluation of ULTALITE®low cost aluminium metal matrix composite based brake drums. *SAE Trans.* **2005**, *114*, 902–907. [CrossRef]
190. Skillingberg, M.; Green, J. Aluminum applications in the rail industry. *Light Met. Age* **2007**, *65*, 8.
191. Pedneault, J.; Desjardins, V.; Margni, M.; Conciatori, D.; Fafard, M.; Sorelli, L. Economic and environmental life cycle assessment of a short-span aluminium composite bridge deck in Canada. *J. Clean. Prod.* **2021**, *310*, 127405. [CrossRef]
192. Kitzmantel, M.; Neubauer, E. Innovative hybrid heat sink materials with high thermal conductivities and tailored CTE. In Proceedings of the Components and Packaging for Laser Systems, San Francisco, CA, USA, 7–12 February 2015; pp. 51–61.
193. Shu, S.; Yang, H.; Tong, C.; Qiu, F. Fabrication of TiCx-TiB2/Al composites for application as a heat sink. *Materials* **2016**, *9*, 642. [CrossRef]
194. Ujah, C.; Popoola, A.; Popoola, O. Review on materials applied in electric transmission conductors. *J. Mater. Sci.* **2022**, *57*, 1581–1598. [CrossRef]
195. Berg, J.S. Composite material advances in the golf industry. *Europe* **2000**, *1*, 7.
196. Sun, Y.; Zhao, Y.; Wu, J.; Kai, X.; Zhang, Z.; Fang, Z.; Xia, C. Effects of particulate agglomerated degree on deformation behaviors and mechanical properties of in-situ ZrB2 nanoparticles reinforced AA6016 matrix composites by finite element modeling. *Mater. Res. Express* **2020**, *7*, 036507. [CrossRef]
197. Rubel, R.I.; Ali, M.H.; Jafor, M.A.; Alam, M.M. Carbon nanotubes agglomeration in reinforced composites: A review. *AIMS Mater. Sci.* **2019**, *6*, 756–780. [CrossRef]
198. Lengauer, W.; Dreyer, K. Tailoring hardness and toughness gradients in functional gradient hardmetals (FGHMs). *Int. J. Refract. Met. Hard Mater.* **2006**, *24*, 155–161. [CrossRef]
199. Farajollahi, R.; Aval, H.J.; Jamaati, R. Effects of Ni on the microstructure, mechanical and tribological properties of AA2024-Al3NiCu composite fabricated by stir casting process. *J. Alloys Compd.* **2021**, *887*, 161433. [CrossRef]