Nano and hybrid aluminum based metal matrix composites: an overview

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Abstract – Aluminium matrix composites (AMCs) are potential light weight engineering materials with excellent properties. AMCs find application in many areas including automobile, mining, aerospace and defence, etc. Due to technological advancements, it is possible to use nano sized reinforcement in Al matrix. Nano sized reinforcements enhance the properties of Al matrix compared to micro sized reinforcements. Hybrid reinforcement imbibe superior properties to aluminium matrix composites as compared with Al composites having single reinforcement. This paper is focused on overview of development in the field of Al based metal matrix with nano and hybrid aluminium based composites.

Key words: Aluminium, Nano, Hybrid, Composites

1. Introduction

In quest to realize advance turbine or aircraft design, the technological development in the field of composite materials provide an opportunity to make a reality. The composite materials have potential to cater the limitations associated with conventional materials. Composite materials are designed and manufactured to solve technological problems for various applications including automotive components, sports goods, aerospace parts, consumer goods and marine applications due to their performance, advantages and possibility to produce light weight components [1, 2].

Aluminium matrix composites (AMCs) with their enhanced strength, improved stiffness, reduced density, improved abrasion and wear resistance offer better alternative to existing materials used for structural, non structural and functional applications [3]. Commonly used reinforcement in AMCs are of micro level, however technological advancement in nano sciences makes it possible to use nano sized reinforcement in metal matrix composites and these are termed as Metal Matrix Nano Composites (MMNCs). “Nanocomposites” were proposed by Choi and Awaji [4], a new material design concept where in second phase nano particles dispersed in matrix to enhance various properties of composite materials. In MMNCs, the reinforcement is in the nanometer range (10^{-9} m) i.e. less than 100 nm which has interaction at

interface due to its increased surface area, this leads to superior material properties. Nano sized reinforcements can significantly improve mechanical strength, creep resistance at elevated temperature, better machinability and higher fatigue life without affecting ductility. Improvement in the properties of MMCs is attributed to the hardening mechanism, fine particle size, uniform distribution, inter particle spacing and thermal stability at high temperature [5–7].

Hybrid composites can have engineering combination of two or more forms of reinforcement like fibers, short fibers, particulates, whiskers and nanotubes. It can have different materials as reinforcement like (SiC, Al_2O_3), (Graphite, SiC) and (Graphite, Al_2O_3), etc. e.g. Car engine block in which graphite and alumina are used in the form of particulates [8–10]. Hybrid metal matrix composites shows improved mechanical properties due to reduction in meniscus penetration defect and reduced formation of inter-metallic component at interfaces because of increased interfacial area [11]. There have been a very few studies available on aluminium (Al) based hybrid composites. A few research studies on Al based hybrid composites are available in which investigations on reinforced Al/Al alloys with hybrid composition of Al_2O_3 fibres + Al_2O_3 particulates, SiC particles + graphite fibres, Al_2O_3 fibres + SiC particles, Carbon short fibres + Al_2O_3 short fibres, $ABO_w(Al_{18}B_4A_{33}) + BPO_p(BaPbO_3)$, $BPO_w + WO_3$ particles, glass fibres + SiC fibres and $ABO_w + SiC_p$ were reported [12–16].

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Table 1. Advanced processing techniques of nano composites [21].

Mechanical processing	Thermo-mechanical processing	Non-equilibrium processing	Room temperature processing
(a) Severe plastic deformation	(a) Hot pressing	(a) Microwave sintering	(a) Electro deposition
(b) Equal angular processing	(b) Hot isostatic pressing	(b) Thermal spray processing	(b) Nano consolidation of self deposition structures
(c) High pressure torsion	(c) Hot extrusion	(c) Plasma spraying	
(d) Shock wave consolidation	(d) Sintering	(d) High velocity Oxyfuel spraying	
(e) Transformation assisted consolidation	(e) Sinter forging	(e) Cold spraying	
		(f) Spark plasma sintering	
		(g) Laser based techniques	

2. Processing of Al based metal matrix nano and hybrid composites

Processing of Metal Matrix Composites (MMCs) mainly classified into two groups namely ex-situ synthesis and in-situ synthesis. In ex-situ synthesis the particles are added into the metal matrix from outside and in in-situ synthesis the reinforcement is realized by chemical reaction or exothermic reaction e.g. exothermic dispersion, reactive hot pressing, reactive infiltration and direct melt reaction [17]. Ex-Situ methods consists of solid state processing and liquid state processing. Solid state includes Powder Metallurgy (PM), Diffusion Bonding, Immersion Plating, Electroplating, Spray Deposition, Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), etc. Liquid state processing includes Stir Casting, Melt Infiltration, Melt oxidation Processing, Squeeze Casting, Compo Casting/Rheo Casting, etc. [18]. Manufacturing processes used for MMCs are also suitable for processing Al based nano and hybrid composites. Several researchers have reported the use of conventional methods such as PM, Stir Casting, Squeeze Casting as well as many other techniques like High Energy Ball Milling, Mechanical Alloying, Pressureless Infiltration, Gas Injection Spray Forming, Spark Plasma Sintering, Ultrasonic Cavitations based solidification, Vortex Process, Sol-Gel synthesis, Laser Deposition, etc. [19, 20].

Viswanathan et al. [21] have reported on the limitation of traditional consolidation techniques which are unable to retain the nano scale grain size owing to the excessive grain growth during processing. Processing methodologies of nano composites is reviewed in an exhaustive way. The various processing routes are presented in Table 1.

Figures 1–8 show the schematic diagram of various processes used in the development of nano composites.

Nano particles have the tendency of agglomeration and clustering, due to high surface energy, attractive Van der-waal's bonding, electrostatic and moisture adhesiveness, which affect its uniform distribution during processing. Cao et al. [5, 7], Yang et al. [19, 20], Li et al. [22], Sunnel et al. and Donthamsetty et al. [23, 24], Narsimha Murthy et al. [25] and Miranda et al. [26] used Ultrasonic Cavitations based method to fabricate nano composite and reported improvement in uniform distribution of nano particles by avoiding agglomeration and clustering in the matrix material.

Zok et al. [27] used extrusion method for consolidation of hybrid metal matrix composite Al-SiC rod/Al alloy. Jang et al. [28] used powder metallurgy method to fabricate nano and

Figure 1. Schematic of equal-channel angular pressing process. ϕ and Ψ are the channel intersection angle and the arc curvature angle [21].

Figure 2. Schematic of high pressure torsion [21].

hybrid composite and reported that the surface properties, changes of nano materials and high aspect ratio up to 1,000 causes clusters of individual fiber into agglomerates.

Figure 3. Microwave sintering [64].

Figure 4. Schematic of a hot isostatic pressing setup [59].

Low power sonication had been used to disperse nano sized fibrous material ultrasonically. Mula et al. [29] used non contact ultrasonic casting method for 2 wt.% $\text{Al}_2\text{O}_3/\text{Al}$ nano composite which resulted in improved mechanical properties because of uniform dispersion of nano Al_2O_3 particles. Figure 9 shows the application of ultrasonic energy to have uniform dispersion of nano reinforcement in aluminium matrix.

Lin et al. [30] used mechanical milling and hot pressing to fabricate Al based nano composite in the form of large billets but this process produces non uniform, bimodal grain size distribution due to the re-crystallization and grain coarsening at elevated temperature. Liu et al. [31] have employed an in-situ

method which uses high pressure to consolidate the nano SiC/Al composite. It was reported that due to large surface area to volume ratio of nano scale reinforcement chemical reaction and diffusion occur easily; hence this method produce well bonded nano composite, but agglomeration could not be avoided completely. Torralba et al. [32] reviewed PM technique for Al matrix composite and have reported the advantages of PM method as low temperature manufacturing which not only avoids strong interfacial reaction but also minimize undesired reaction between Al matrix and reinforcement. PM route also makes it possible to produce MMCs which are not possible by other method e.g. SiC/Ti alloy composites. Woo and Zhang [33] have reported use of high energy ball milling and powder metallurgy method to produce Al based nano composites. Eutectic reaction occurred during milling increases the sintering rate due to increased diffusion rate for the composite powder which in turn gives finer microstructure, high hardness and less pores. Zhang et al. [10], Sureshababu et al. [11], Feng et al. [12] and Geng et al. [34] have used squeeze casting to fabricate Al based hybrid composite which distribute nano particles homogeneously that increased strength and resistance to fracture propagation. Reddy et al. [35] produced aluminium matrix hybrid ($\text{Al}_3\text{Ni}/\text{Al}_2\text{O}_3$) nano composite by mechanically activated solid state combustion in-situ method without affecting nano-structure. It was reported that in-situ processed composite are technologically considered to be more advanced composites than ex-situ processed composite materials. Physical state of reactant phase form the basis for grouping in-situ methods such as liquid-liquid, liquid-solid and solid-solid reactions e.g. Direct Melt Oxidation (DIMOX), Exothermic Dispersion (XD) and Self Propagating High Temperature Synthesis (SHS). Bustamante et al. [36] have produced multi-walled carbon nano tube (MWCNTs) reinforced Al matrix nano composite by mechanical milling followed by pressureless sintering at 823 K under vacuum. No damage occurred to multi-walled carbon nano tube during processing. Milling time vol.% of MWCNTs reinforcement influenced mechanical properties of nano composites. Laha et al. [37] have reported on limitation of processing of carbon nano tube (CNTs) reinforced metal matrix bulk nanocomposite. Incorporating CNTs in MMCs is a difficult task and it is further difficult to achieve homogeneous distribution and effective retention of CNTs in the matrix after processing. Effective interfacial bonding between matrix and reinforcement is desirable to transfer load in metal matrix nanocomposite. It is challenging to develop processing techniques for CNTs. CNTs reinforced in Al matrix composites were successfully fabricated by Plasma Spray forming and High Velocity Oxy-fuel Spray forming. Both the techniques are capable of producing composites with intact and undamaged MWCNTs with improved properties. Wang et al. [38] have prepared Al matrix composite by in-situ Direct Melt Reaction technique. Analysis showed uniform dispersion of Al_2O_3 and clean interface between particles and Al matrix. In this process performance of composite showed improvement as there were large amount of high density dislocations and extensive fine sub-grains around Al_2O_3 particles and no impurity existed between particles and matrix. This composite reported to possess isotropic properties. Fully dense Al based nano composite by combining

Figure 5. Schematic of sinter forging process [60].

Figure 6. Schematic of plasma spraying operation [61].

two Severe Plastic Deformation (SPD) processes; planetary ball milling for mixing powders and back pressure equal-channel angular pressing for consolidation [39]. Thus produced carbon nano particles/Al and nano $\text{Al}_2\text{O}_3/\text{Al}$ composite exhibit effective particle distribution. Joo et al. [40] have reported use of high pressure torsion (SPD) processing to produce nano tube/Al composites. This has developed homogeneous nano structures with high angle grain boundaries due to its ability to impose extremely high strain and hydrostatic pressure. Xue et al. [41] have fabricated diamond + SiC/Al composite with high volume fraction by gas pressure infiltration. The results showed that the fine SiC particles occupy the interstitial

Figure 7. Schematic of high velocity oxy-fuel spraying [62].

position around coarse diamond particles. Lee et al. [42] have reported on Friction Stir Processing (FSP) is promising method to produce Al matrix composite. FSP induce severe plastic deformation to promote mixing and refining of constituent phases in the material and hot consolidation helps to form fully dense solid. It is a versatile technique which helps to control the microstructure and mechanical properties by optimizing the tool design and FSP parameters. Nandpati et al. [43] have used friction stir welding process (FSWP) to produce nano SiC reinforced AA6061 composite. The low weldability of Al restrict the use of fusion welding method to weld parts used in aircrafts and other applications. This technique has significant potential to join Al alloys and composites with high strength joints.

Wong et al. [8], Gupta et al. [44] have reported successful synthesis of hybrid composite (Al/Fe + SiC and Al/Fe + Ti respectively) by using Disintegrated Melt Deposition (DMD) followed by hot extrusion. This method has produced composite with uniform distribution with good interfacial integrity between reinforcement and matrix and absence of reaction product at the iron wire/Al interface. Reddy et al. [45] have

Figure 8. Schematic of spark plasma sintering setup [63].

Figure 9. Ultrasonic cavitations based nano composite manufacturing set up [19].

used microwave processing to fabricate hybrid metal matrix composite for electrical sliding contact application. Microwave sintered metal matrix composite revealed higher relative density and hardness compared to traditionally sintered composites. Microwave sintering is potentially better method to produce composites.

Thakur et al. [46] have manufactured Al/SiC nano composite by using energy efficient microwave assisted powder metallurgy route. Use of PM coupled with hybrid microwave sintering and hot extrusion resulted in uniform distribution of nano sized SiC particles, but some minor clustering and minimal porosity occurred.

One of the problem encountered in processing of Al based nano and hybrid composite by liquid state route is settling of particles due to density difference between matrix and

reinforcement. Stir Casting method provide solution to avoid settling of particles.

Rajan et al. [47], Ramesh et al. [48] have used Stir Casting method to produce Al based composites. Schultz et al. [49] have fabricated nano $\text{Al}_2\text{O}_3/\text{Al-Mg}$ alloy composite by stir casting method. It was reported that conventional stir mixing followed by casting is one of the most economical techniques available to produce MMCs. Nano sized reinforcement of interest are not wet by molten metal during stir mixing and nano particles have tendency to cluster, but reactive wetting combined with high shear stir mixing has the potential to overcome this problem. Hashmi et al. [50] have discussed the use of stir casting method to produce MMCs and difficulties associated with getting a uniform distribution, good wettability and low porosity. The stir casting method is cost effective, simple and flexible. The method can handle large quantity of production, minimizes the final cost of product and allows large sized components to be fabricated.

Kumar and Kruth [51] have focussed on application oriented composites and very new idea of using rapid prototyping (RP) technology to produce composites. Out of various techniques available only some have been used for fabricating composite like Selective Laser Sintering/Melting (SLS/SLM), Laser Engineered Net Shaping (LENS), Laminated Object Manufacturing (LOM), Stereo Lithography (SL), Fuse Deposition Modelling (FDM), 3D Printing (3DP) and Ultrasonic Consolidation. Rapid Prototyping initially used for polymeric composites but it can be used to produce parts made of metal matrix composites. It was reported that SLS has potential to produce MMCs and nano composites. Li et al. [65] have successfully used AC pulse electro deposition method to fabricate Ni/GO nanocomposites. The nanocomposites produced reported have enhanced plasticity.

The second secondary processing of AMCs further improves their performance. Hot extrusion is secondary forming process often used to improve properties of AMCs for industrial applications. It enhances the UTS and % elongation of Al matrix composites compared to as-cast composites mainly due to decreasing the amount of porosity. It is reported to that with extrusion ratio of 18:1 at 420 °C gives optimum value for UTS and elongation of Al composites [66]. Hot extrusion helps to disperse the reinforcement homogeneously in Al matrix and also gives final size of Al grain considerably fine. In as-cast aluminium matrix composites poor restrict their properties and applications. The ductility of AMCs affected by parameters like microstructure, distribution of reinforcements and porosity. To improve ductility secondary processing of the discontinuously reinforced AMCs become essential. Hot extrusion is better method to for this purpose which helps in breaking particle agglomerates, distributing particles homogeneously, reducing porosity, improving particle matrix bonding and refining matrix structure. This can results in better mechanical properties compared to as-cast composites [67].

The overview of the different manufacturing methods show that there is a need to find, select and decide on the use of the most suitable manufacturing method to process Al based nano and hybrid composites. The manufacturing process that gives uniform distribution of nano particles/hybrid reinforcement without clustering and agglomeration as well as without

damaging particles is preferred. The process should produce the composite which has better interfacial bonding, better wettability, non reactive and clean interface. The selection of suitable manufacturing method for MMCs based on ability to produce fine grain, reduced grain growth, ability to produce near net shapes and low temperature of processing. The effective parameter control, optimized parameters, and ability to process large volume fraction of reinforcement are the factors that affect the decision on selection of manufacturing method. The other factors such as superior mechanical properties, low thermal expansion, ability to handle large production rate, ability to produce large sized parts, safety of production and commercial viability, are required to be considered while selecting the manufacturing process.

3. Properties of Al based metal matrix nano composites

Prime objective of manufacturing and using composite materials is that their properties can be tailored by varying the nature of the constituents, their volume fraction and processing routes. Al matrix composite refers to the class of light materials having superior combination of properties such as high strength, high stiffness, low density, improved elevated temperature properties, etc. AMCs can pose tough competition to existing monolithic materials and offer strong alternative as material to be used in engineering applications.

Commonly used ceramic reinforcement such as SiC and Al_2O_3 affect the physical, mechanical, thermo-mechanical and tribological properties of AMCs. AMCs have better mechanical properties over unreinforced Al/Al alloy due to change in matrix microstructure [3, 52].

With the invent of nano sized reinforcement (CNTs, nano particles, etc.), it can be used in Al matrix composites due to phenomenal properties which they exhibit. Nano sized reinforcement have superior properties. e.g. CNTs have stiffness of about 1,000 GPa, strength 100 GPa and thermal conductivity 6,000 W/m K depending on its structure. It was shown that with the addition of small wt.% (0.05 wt.% and 0.1 wt.%) of CNTs in LM24 Ultimate Tensile Strength (UTS) was reported to be increased by 8% and yield strength increased by 32% with corresponding decrease in elongation by 16%. This has happened because of CNTs pinning and hindering both grain boundaries and dislocation migration during applied load. The results obtained were in the line with the expectation that small grain size would result in a larger yield strength and lower elongation in accordance with Hall-Petch criteria [26].

Milling time and volume fraction of MWNCTs have an important effect on the mechanical properties of Al based nano composites. With increase in milling time from 0 to 1 h and MWNCTs volume fraction from 0 to 0.75%, yield strength increased upto 300% compared to sample without MWNCTs and unmilled. Hardness of the composite is also increased with increase in MWNCTs reaching the maximum value of around 77 Hv with 2 h of milling time and 0.75 vol.% of reinforcement [36].

The hypothesis for strengthening mechanism of MWCNTs reinforced nanocomposite consist of four points (a) Obstruction of dislocation motion by MWNCTs; (b) Wetting of MWNCTs by Al matrix; (c) Thermal mismatch between MWNCTs and Al matrix; (d) Formation of a transition layer between the MWNCTs core and the Al matrix. TEM observation confirms the absence of dislocation within the nanocomposite. Wetting is the necessary condition for interfacial shear transfer however wetting is not possible due to large difference in surface energies of Al matrix and MWCNTs and difference in surface tension values. The surface tension of aluminium is 865 N/m and MWNCTs 100–200 N/m. The volume contraction of Al after heat treatment may contribute to the mechanical adhesion of the MWNCT to matrix. TEM observation showed the formation of transition layer seems to be very rough. MWNCTs are immersed in the Al matrix and the roughness being the source of stress transfer between Al matrix and MWNCT. Further additional work is required to understand the strengthening mechanism operating in the Al based composite. No literature is available on the wetting phenomena and interfacial properties of Al-CNT system [36, 37, 40].

Aluminium reinforced with nano sized SiC particles with varying vol.% (5 vol.%, 10 vol.% and 20 vol.%) increased the micro-hardness of the composites. It is evident that the increase in volume fraction of SiC particles have resulted into higher micro-hardness of composite. The increase in hardness is attributed to the use of high temperature and pressure which in turn enhanced adhesion between Al matrix and SiC nano reinforcement. At high temperature SiC/Al interface become reactive which produces aluminium carbide Al_4C_3 and Si. The excess Si harden the Al matrix [30]. Al/SiC system is studied by many researchers extensively because of their compatibility with each other. Most of the reported research work on Al/SiC showed use of micron sized particles as reinforcement. Due to technological development use of nano SiC as reinforcement generated interest among researchers. Addition of SiC in Al matrix improves its mechanical properties considerably. It was reported that on 2 wt.% of nano sized SiC in A356 matrix improved its yield strength by 50% which is significantly better than Al alloy with same percent of micro particle reinforcement [47]. But very little work done so far on this system of nano composite.

Fly ash from thermal power plant is also used as nano reinforcement in Al alloy matrix to enhance mechanical properties. The use of nano sized fly ash particles (1 wt.% to 3 wt.%) increased hardness of AA2024 from 75 Hv for 1 wt.% to 114 Hv for 3 wt.%. Presence of harder fly ash nanoparticles, higher constraint to the localized matrix deformation during indentation, harder $CuAl_2$ phase in the matrix and refined grain structure of matrix attributed to increase in hardness. Furthermore cooling of composite after processing to room temperature; mismatch strain due to the difference of coefficient of thermal expansions between the nano fly ash reinforcement and Al matrix develop high density dislocations which strengthens the matrix. Nano fly ash obstruct the movement of high density dislocations resulting in improvement of hardness. Compressive strength of nano fly ash/Al composite

Figure 10. TEM of Aluminum Alloy- Al_2O_3 nanocomposites produced by liquid and solid based methods respectively. (A) Stir cast A206- 2 vol.% Al_2O_3 (47 nm) nanocomposite. (B) Powder metallurgy based Aluminum alloy-15 vol.% Al_2O_3 nanocomposite [58].

increased with increase in wt.% of nano fly ash. The strength of AA2024 alloy is 289 Mpa and it is increased to 345 MPa for 3 wt.% fly ash/AA2024 composite. The transfer of load from matrix to the particulate, the interaction between nano sized particulates and individual dislocations, reduction in matrix grain size and generation of high density dislocations in the matrix are reasons for increased compressive strength [25].

There are two reasons to dislocation pile up; grain boundaries and formation of grain boundary ledges because of multi glide plane agglomeration. Under the applied stress multi-glide system due to induced multi directional thermal stresses during processing develop dislocations in several directions. The increasing amount of grain boundaries and grain boundary ledges act as obstacle to dislocation movement to increase strength of composite [25, 38]. Figure 10 shows TEM of Al alloy/ Al_2O_3 nano composites [58].

Graphene is one atomic layer thick sheet of carbon. It has two dimensional honey comb structure. Graphene has remarkable thermal (Thermal conductivity – 5.3×10^3 W/mK), electrical and mechanical (Intrinsic Strength 130 GPa, Young's Modulus – 1.0 TPa) properties which makes it a superior material for reinforcement in AMCs. Due to graphene's excellent properties it has ability to replace CNTs as a first choice for reinforcement in nanocomposite materials. Graphene has many advantages over CNTs like higher specific surface area ($2,600 \text{ m}^2/\text{g}$), has less tendency to twist, ability to disperse in matrix easily, higher strength and stiffness [68–70]. Graphene has fracture strength of 125 GPa which makes it an ideal material for reinforcement in AMCs. It has been reported that with only 0.3 wt.% of GNS (Graphenes Nano Sheets) the tensile strength of AMCs enhanced by 62% compared to unreinforced aluminium matrix [71].

4. Properties of Al based metal matrix hybrid composites

Reinforcement in hybrid form to improve properties of composites, which gives high degree of freedom in material

design. The properties of hybrid composites are more excellent than those composites with single reinforcement due to hybrid effectiveness produced by combination of reinforcement in hybrid composite. Al matrix composite when reinforced with hybrid combination of SiC and Graphite particulates produce excellent mechanical and tribological properties. SiC in Al matrix helps in strengthening and graphite reinforcement aids in lubrication. But SiC causes ductility of composite to decrease and graphite decrease whole mechanical capability of composite. Heat treatment at 630°C of Al/SiC + Gr composite improve its hardness as a result of interfacial reaction at matrix and reinforcement interface with the formation of reaction product Al_4C_3 [9].

The addition of SiC whiskers is more effective in improving the strength and ductility of composites than addition of SiC particulates. The investigations on SiC reinforcement have found that particle size less than $10 \mu\text{m}$ gives better mechanical properties. Hence hybridization of SiC_w + SiC nano particulates can further enhance properties of composites [10].

Though Aluminium borate whiskers ABO_w ($\text{Al}_{18}\text{B}_4\text{A}_{33}$) are of low cost they possess superior stiffness and strength. ABO_w reinforced Al matrix composite can be easily formed and machined by conventional techniques. These composites find applications in many fields such as automobile shaft and brake rotors. WO_3 (Tungsten Oxide) is used in functional materials, hard alloy and radiation protection materials. To exploit the advantages of these materials, as reinforcement in composites, the fabrication of $\text{Al}/\text{ABO}_w + \text{WO}_3$ hybrid composite is reported for the protection of semiconductor devices for X-ray. It was reported that elastic modulus, UTS and yield strength increased from 69 GPa to 96 GPa, 47 MPa to 287 MPa and 24.27 to 250 MPa respectively than the matrix material. But ductility of hybrid composite decreases and lower than the matrix material. However as compared to other composites elongation is appreciable. Hybrid composite exhibit high potential to be used for various applications because of its superior properties [12].

Another composite for radiation protection application reported, was Al/ABO_w ($\text{Al}_{18}\text{B}_4\text{A}_{33}$) + BPO_p (BaPbO_3). It showed that BPO_p reacts with Aluminium forming a coating

(100 μm thick) on the surface of ABO_w . This coating consist of Ba, Pb and Al. Pb grain size of 30 nm. This hybrid composite have better mechanical properties compared with Al/ ABO_w composite. It was reported that tensile strength and young's modulus of Al/ $\text{ABO}_w + \text{BPO}_p$ increased to 224 MPa and 104 GPa respectively compared to Al (Tensile strength 64 MPa and Young's modulus 69 GPa) and Al/ ABO_w (Tensile strength 138 MPa and Young's modulus 107 GPa). The increase in ductility also is reported due to Pb phase [13].

Hybrid composites fabricated using in-situ process magneto-chemical reaction between $\text{A356-Zr}(\text{CO}_3)_2$, consist of $\text{Al}_2\text{O}_3 + \text{Al}_3\text{Z}_2$ nano particulates. The particle distribution in the matrix was uniform. It was indicated that mechanical properties UTS, yield strength and hardness reached to higher values of 393.87 MPa, 339.74 MPa and 139.8 N/mm² respectively compared to composite obtained without the assistance of pulsed magnetic field. The change in elongation is almost negligible for this hybrid composite [17].

Successful fabrication of hybrid composite which consist of 6,061 Al/5 vol.% $\text{ABO}_w + 15$ vol.% of SiCp has reported. For this system of hybrid composite semi solid stirring technique was used. ABO_w with a diameter of 5 μm , length 10–30 μm and SiC particles within range of 8–14 μm used. Tensile strength of hybrid composite fabricated at different stirring temperature and time were reported. Stirring temperature selected were 680 °C, 650 °C, 640 °C and 630 °C, and stirring time 20 min and 30 min. UTS of the composite fabricated at 640 °C was 293 MPa, 680 °C – 186 MPa, 650 °C – 251 MPa and 630 °C – 228 MPa. The increase in the UTS for 640 °C was 57.5%, 16.7% and 28.5% more compare to UTS at 680 °C, 650 °C and 630 °C respectively. The elongation of composite fabricated at 640 °C – 4.6% was higher by 50%, 23.9% and 30.4% than composite at 680 °C – 2.3%, 650 °C – 3.5% and 630 °C – 3.2% respectively. Increase in stirring time significantly increase UTS and elongation. At stirring time 20 min UTS- 214 MPa and elongation 2.5%, for 30 min stirring UTS 293 MPa and elongation 4.6% were reported [16].

In 2024 Al matrix, reinforced with SiC_w and SiC_p, hybrid composite SiC_p leads to increase in the wear resistance, elastic modulus and in CTE (coefficient of thermal expansion) while SiC_w improves strength and ductility. It was observed that hybrid composite showed increasing trend in UTS and elastic modulus at the same time trend in % elongation decreasing for increasing SiC_p wt.% (2%, 5% and 7%) at 20 wt.% SiC_w [34].

5. Applications of Al based metal matrix nano and hybrid composites

There is huge potential for use of Al based metal matrix composite due to the superior properties and high degree of tailorability that they confers. It is seen that by using nano sized particulates as reinforcement as well as hybridization of reinforcement one can tailor and provide excellent properties to Al based composites compared to Al based alloy and micron sized singly reinforcement reinforced Al based composites. Various functionalities could be designed through

appropriate selection of constituents in Al based hybrid and nano composites.

5.1. Structural applications

Strength and stiffness are the two most important challenges for structural applications. Al based composites provide competitive level of specific strength and stiffness. In addition to excellent specific stiffness and strength, structural application requirements are high bearing strength, resistance to aggressive environments, resistance to out gassing, good through thickness thermal conductivity, good wear resistance, high dimensional stability, good impact and erosion resistance, resistance to burning and high temperature application. Al based composites provide better response in these areas. The use of Al based composite in fracture critical application provides sufficient evidence for the same e.g. tyre stud, drive shaft in Chevrolet S-10. Improved properties can be achieved with more uniform distribution and finer particulate sizes [53].

5.2. Thermal applications

High thermal conductivity, specific thermal conductivity and CTE (coefficient of thermal expansion) are important properties for thermal applications like substrates for computer processor chips, power semiconductor devices used in telecommunications, sub components in aerospace system and automotive applications. Al based composites can be useful for these applications e.g. Al/SiC composite used for satellite microwave system, flip chip lid in networking and telecommunication and, intake and exhaust valve in Toyota Altezza [53]. Development of Al based hybrid composites for high temperature application reported, have SiC, Al_2O_3 and TiB_2 as reinforcements [54]. Nano sized SiC reinforced in aluminium exhibit better dimensional stability, hence can be used for thermal applications that requires high dimensional stability [55].

5.3. Precision applications

Many precision applications require exceptional resistance to distortion that occurs due to thermal and mechanical load such as hard disk drive, video recording head, atomic force microscope support frame, robotic arms, satellite antennae and high speed manufacturing equipments. Al based composite provide improved resistance to this requirements e.g. space shuttle mid fuselage main frame, Hubble space telescope antenna [53].

5.4. Wear resistance

Wear resistance is an important requirement for Al based composite for many applications such as piston and cylinder bore in engine, especially brake system (disk, rotors, pads and callipers) in automotive area. Al based composite offer high thermal conductivity, good wear resistance, reduced braking noise, low density for fuel economy, better acceleration and reduced braking distance. Al/SiC composite used for the rear brake drums of Volkswagen Lipo 3L and the Audi A2.

Table 2. Properties of Al based metal matrix nano and hybrid composites.

Material	Particle size (µm/nm)	Vol.%/Wt.%	Elastic modulus GPa	UTS MPa	Yield strength MPa	% Elongation	Hardness	Ref.
Al/SiC + Gr		20 wt.%, 6 wt.%			153			[9]
2024Al alloy/SiC _w + SiC _p	0.3–0.6 µm, 10–28 µm length 35 nm	20 vol.%, 0–7 vol.%	150–200	450–600	275–550			[10]
Pure Al/WO _{3p} + ABO _w	18 µm 0.5–1 µm, 10– 30 µm length	3 vol.%, 22 vol.%	96	287.30	250.7	1.66		[12]
Pure Al/ABO _w + BPO _p	0.5–1 µm, 10–30 µm length 0.2–0.5 µm	20 vol.%, 5 vol.%	104	224		3.5		[13]
Pure Al/ABO _w	0.5–1 µm, 10–30 µm length	20 vol.%	107	138		0.48		[13]
PureAl/WO _{3p} + ABO _w	3 µm 0.5–1 µm, 10–30 µm length	WO ₃ ABO _w 3 vol.%, 22 vol.%, 5 vol.%, 20 vol.%, 7 vol.%, 18 vol.%		280 260 200		1.5 1.3 1.0		[14]
6061 Al/ABO _w + SiC _p	0.5–1 µm, 10–30 µm length	5 vol.%		293 (at 640° C) 186 (at 680 °C) 251 (at 650°C) 228 (at 630 °C)		4.6 2.3 3.5 3.2		[16]
	8–14 µm	15 vol.%		293 (at 30 min. stirring) 214 (at 20 min. stirring)		4.6 2.5		
A356/Al ₂ O ₃ + Al ₃ Zr	0.08–13 µm	20 wt.%						[17]
Without magnetic field assistance				354	278.95	4.85	108 N/mm ²	
With magnetic field assistance				393.87	339.74	4.72	139.8 N/mm ²	
AA 2024/Fly ash	23 nm	1–3 wt.%		289–345 Compressive strength			75–114 Hv	[25]
LM24/Cu-CNT nano fillers	1–100 µm	0.05–0.1 wt. %		150		4.81		[26]
Al/SiC	25 nm	5 vol.%, 10 vol.%, 20 vol.%					90 Hv 130 Hv 170 Hv	[30]
Al/SiC _w + SiC _p T6	0.3–0.6 µm, 10–28 length 35 nm	20 vol.%, 2–7 vol.%	124–127	513–620		0.77–0.83		[34]
Al/SiC _w	0.3–0.6 µm, 10–28 length	27 vol.%	126	613		0.8		[34]
Pure Al/MWCNTs		0.25–0.75 vol.%		198.5–330.8	126.1–230.5		57–77 Hv	[36]
Al/Fe mesh/SiC	25 µm		75.2	214	191	3		[45]
Al/Fe mesh			76.7	168	151	4		[45]

Al/SiC Brake disks in Intercity Express (ICE) high speed train in Germany [53].

Nano composite with SiC, SiO₂, TiO₂, BN₃ and diamond within matrix materials such as Al, Ni and Fe finds application in automotive industry and have a striking impact on car bodies and components [56].

6. Issues and challenges in nano and hybrid composite

Nano and hybrid composites both have improved properties compared to monolithic materials and single reinforcement micro particle composites. Though they provide new avenues, there are many issues and challenges to make them useful in engineering applications and commercially viable for wide spread choice.

Various issues in nano and hybrid composites are related to (a) fabrication/processing techniques to produce uniform distribution of reinforcement in matrix and interfacial bonding, (b) formability due to reduced ductility, (c) improvement in mechanical properties with respect to volume fraction and particle size; also to understand strengthening mechanisms and role of individual reinforcement in hybrid composites, (d) tribological properties which include wear and friction, (e) use of composite in corrosive media, (f) thermal conductivity, thermal expansion and dimensional stability at high temperature [55].

Performance of Al based metal matrix composite materials depend on volume fraction and particle size. There is a need to improve and modify existing processing methods to be used in fabrication of Al based nano and hybrid composite. Also there is a need to develop new methods. Formability of Al based metal matrix composites is an important issue as addition of reinforcement particles reduces the ductility of composites, which makes them unsuitable for forming. There is need to develop composite without affecting its ductility. Weight loss of composite depends strongly on volume fraction and particle size. To obtain improved mechanical, tribological and other properties for Al based composites, there is need to focus on processing techniques, process parameters, process control, handling of large volume fraction, particle size, interface, method to improve wettability and uniform distribution, extreme service condition. There is a need to develop composite without compromising toughness, produce reinforcement particles with low cost, improve upon secondary processing techniques for large volume production with low cost, recyclability and commercial viability [57]. Table 2 presents the properties of aluminium based metal matrix nano and hybrid composites.

Especially there is need to address environmental and cost issues related to aluminium matrix nano and hybrid composites. This issues restrict their wide spread use as alternative light weight materials. The environmental conditions affect the performance of Al matrix composites. The corrosion behaviour of aluminium matrix composite in various environments is an important selection criteria for Al and its alloys as a matrix for particular purpose. Reinforcements (particulates and fibers), conditions of processing of AMCs can cause accelerated corrosion of Al alloys matrix composites as

compared to unreinforced Al alloys. The different forms of corrosion associated with Al matrix composites are pitting corrosion, galvanic corrosion, crevice corrosion, stress corrosion cracking, corrosion fatigue and tribo corrosion. The primary sources of corrosion for Al matrix composites are galvanic corrosion between matrix and reinforcement, chemical degradation of interfaces and reinforcements, corrosion due to processing conditions of Al matrix composites and resulting microstructures. AMCs with corrosion resistance can be produced by controlling microstructures of composites, processing conditions and interaction at the interface of composites [72].

Cost of fabrication of AMCs with nano sized reinforcement is generally very high. This is due to the higher cost of obtaining nano sized reinforcement. Though various synthesis and production techniques of nano reinforcement (particles and fibers) have been developed but there is a need to develop the methods to produce nano sized reinforcement in large quantity and which have affordable cost. There exist a need to develop processing techniques for nano and hybrid AMCs which gives uniform distribution reinforcements, preserve the nanostructure in end product without excessive grain growth and able to produce it in bulk quantity to reduce the cost. The process control and optimization of process parameters plays an important role in reducing the cost of production of nano and hybrid AMCs.

7. Conclusion

Most of Al based nano and hybrid composites developed are at research stage only. These composites have great future due to their superior performance. These composites are anticipated to have substantial applications in automobiles, aerospace, marines, sporting goods, etc. Nano sized reinforcement is key element in the development of nanocomposites. Synthesis and production of nano powders at affordable cost will make the use of nanocomposite popular in future. The challenging aspect of nano and hybrid composite manufacturing is the ability to create nanostructure materials having novel properties at macroscale because manufacturing techniques strongly affect the morphology and materials properties at nano meter level. Agglomeration and clustering of nano sized reinforcement is prominent in manufacturing nano composites which affect the uniform distribution of it in matrix material. Ultrasonic probe assisted cavitation method is one of the promising method to address this problem and successfully used by the researchers to manufacture bulk nanocomposite. The conventional processing methods have strong limitation to preserve nanostructure in the final product due grain growth. So development of suitable consolidation and densification techniques for nano and hybrid composites is need of an hour. Handling of nano reinforcement is a challenging task as ultra-fine nano particles have high surface area and are susceptible to contamination due to their high surface activity which in turn degrades physical, chemical and mechanical properties of AMCs. To harness nano size effect to the fullest extent handling of nano reinforcement with utmost care is required.

This work has attempted to present one overview and focus on importance of Al based metal matrix nano and hybrid composites.

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