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A REVIEW ON THE FABRICATION TECHNIQUES OF ALUMINIUM MATRIX NANOCOMPOSITES

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Abstract

In recent years, metal matrix composites have been considered as materials that offer better mechanical properties compared to conventional alloys. Recently, the developments of metal matrix nanocomposites (MMNCs) have become more attractive in various applications. However, the synthesis of MMNCs by conventional casting method has shown a limitation due to low wettability of the reinforcement phase by the molten metal. This paper is aimed at reviewing the best result techniques to fabricate the aluminium matrix nanocomposite (AlMNCs). However, each of these techniques has their own advantages and disadvantages. This review concludes powder metallurgy (PM) as the best technique for mass production and cost effectiveness.

Keywords: Aluminium matrix nanocomposites, metal matrix nanocomposites, fabrication techniques, powder metallurgy

Abstrak

Sejak kebelakangan ini, komposit matriks logam telah dianggap sebagai bahan yang menawarkan ciri-ciri mekanikal yang lebih baik berbanding aloi konvensional. Baru-baru ini, perkembangan nanokomposit matriks logam (MMNCs) telah menjadi lebih menarik dalam pelbagai aplikasi. Walau bagaimanapun, sintesis MMNCs dengan menggunakan teknik acuan konvensional telah menunjukkan had yang kena dibayar kepada kebolehbasahan rendah fasa pengukuhan dengan logam lebur. Kertas kerja ini bertujuan untuk mengkaji teknik hasil yang terbaik untuk mereka-reka yang nanokomposit matriks aluminium (AlMNCs). Walau bagaimanapun, setiap satu daripada teknik-teknik ini mempunyai kelebihan dan kekurangan mereka. Kajian ini menyimpulkan bahawa serbuk metalurgi (PM) sebagai teknik terbaik pasti untuk pengeluaran besar-besaran dan keberkesanan kos.

Kata kunci: Matriks aluminium nanokomposit, matriks logam nanokomposit, teknik fabrikasi, serbuk metalurgi

1.0 INTRODUCTION

Aluminium (Al) matrix composites exhibit higher mechanical properties than unreinforced Al alloys and has been widely studied since 1920s. Due to their lightweight, high Young's modulus, high specific strength and high wear resistance, it had been used for wide range of applications such as sporting goods, electronic packaging, amours, nuclear, biotechnology, aerospace, marine, automotive and transport industries [1-4]. Furthermore, the advantages of Al and its alloys over other composite matrices are its high specific strength and stiffness, good damping capacities, dimensional stability and good machinability. To strengthen the metal matrix, it has become an interest to use nano-sized ceramic particles, while maintaining good ductility, high temperature creep resistance and better fatigue [5]. Recently, metal matrix nanocomposites (MMNCs) have become more attractive in various applications because of better mechanical properties over conventional reinforced microparticles. Nanocomposites are composite material that has at least one of its dimensions in the size of less than 100 nm [6]. Low wettability of ceramic nanoparticles with the molten metal matrix is the main issue to fabricate the MMNCs, which does not allow the production of MMNCs by using usual casting processes. In fact, small powder aggregates are prone to produce cluster which can lose the ability to be dispersed homogeneously in the matrix for an optimal strengthening potential [7]. In order to overcome this issue, several alternative techniques have been proposed.

2.0 ALUMINIUM (Al) ALLOY AND AVAILABLE REINFORCEMENT

Various species of nano-sized oxides (Al_2O_3, ZrO_2, MgO, $FeTiO_3$), and carbides (SiC, B_4C) have been employed as reinforcement agents due to low density and melting point, very good specific strength and the thermal conductivity of Al [7-8]. Carbon nanomaterials, such as fullerenes, carbon nanotubes, and graphenes have been well attended as reinforcements for the Al matrix composites, due to their lightweight nature and superior strength/stiffness stemming from strong sp2 C—C bonds [9]. Recent work in the field of carbon was in the discovery of carbon nanotubes (CNTs) by Iijima in 1991 although CNTs might have been synthesized in 1960 by Bacon. A multi-walled carbon nanotube (MWCNT) is fabricated of many single-walled carbon nanotubes (SWCNT) structured in a concentric manner [10]. Based on size and shape as well as their excellence in mechanical properties such as high elastic modulus, tensile strength and aspect ratio, SWCNTs and MWCNTs have been accepted as new kinds of reinforcement materials for the production of novel MMC in the scientific community [11-12]. Silicon carbide nanowires (SiCNWs) have been attracting considerable attention as a novel type of reinforcement filler due to their outstanding properties such as high thermal stability, high thermal conductivity, superior mechanical properties and chemical inertness. However, the improvement in material properties by using SiCNWs as fillers in metal matrix composites has not been thoroughly studied yet [13].

3.0 PROCESSING TECHNIQUES OF ALUMINIUM MATRIX NANOCOMPOSITES (AlMNCs)

The processing technique to fabricate aluminium matrix nanocomposites (AlMNCs) can be classified into three main groups:

i. solid state processes include high energy ball mill and powder metallurgy (PM) techniques with modifications in the processing step such as, hot pressing, hot isostatic pressing (HIP), cold pressing followed by sintering treatment and extrusion [7];
ii. liquid-state (casting) processes include stir casting, ultrasonic-assisted casting; and
iii. semi-solid processing includes a combination of rheocasting and squeeze casting and semi-solid route stir casting.

The restrictions of the second and third groups occur from difficulties in combining the two phases thoroughly, hard determination of critical temperature for infiltration, issues due to fluidity and/or wettability at matrix-reinforcement interface and producing harmful reactions at the interface [8].

3.1 Solid State Process

3.1.1 High Energy Ball Milling

Several solid production methods were developed to fabricate AlMNCs. In particular, different powder metallurgy (PM) techniques were successfully performed in this field. Some papers discussed on high-energy ball milling known as mechanical alloying (MA) in which a PM technique is incorporated in repeated cold welding, fracturing and re-welding of particles in a high energy ball mill. This practice is of primary importance since it allows a better distribution of nano-powder into the composite by breaking up the ceramic clusters [7]. It is important to note that mechanical properties of mechanically alloyed products strongly depend on the consolidation parameters and milling time. Although there are different methods to compact powder, hot pressing produces net-shape and cost-effective procedures with controlled microstructure and mechanical properties [8].

Al powder (99.8% pure) and Al_2O_3 powder (99.99% pure, 50 and 150 nm sizes) are combined under argon atmosphere inside a glove box to reduce any contamination. High-energy milling of powder is conducted to produce the composite powder which upholds a ball to powder weight ratio of 10:1. About 0.5–1.0wt.% of stearic acid is used in which stearic acid is applied as a process control agent (PCA). Testing of the mechanically milled powder has established a uniform distribution of the reinforcement phase. This has been performed for volume contents up to 50% and particle sizes up to 50 nm [14].

3.1.2 Consolidation Route

The synthesis of two nanocomposite systems of (Al-20wt.%Al_2O_3) and (Al-10wt.% Al_2O_3-10wt.% ZrO_2) was conducted by grinding under argon gas atmosphere at 300rpm milling rotation speed and ball to powder ratio of 10:1. Stearic acid (PCA) is used to prevent the aggregation of powder during milling. In order to achieve high dense samples, consolidation of the milled particulates is performed in two stages including pressing and sintering of the compacts. Pressing the powder is done with the applied pressure of 600MPa and 5 min of the load hold time. For sintering, the compressed powder was kept at 600°C for 45min and nitrogen gas was applied to avoid oxidation of Al. As a result, the density of the green compacted powder is lower than the density of sintered compacted powder, which may be attributed to the reduction of pore space during sintering process and/or due to grain refining. Sintering process plays an important role in obtaining higher density materials. Furthermore, the microhardness increased after the addition of reinforcement particles and milling, which can be attributed to some reasons. Increasing the high energy ball milling duration will achieve higher deformation and increases work hardening of the powder. Furthermore, the addition of hard reinforcing particles might improve the work hardening rate of the matrix, resulting in increase in hardness [15].

SiCNWs and pure Al metal powder are mixed in different wire/Al ratio varying from 5% to 15% by volume. In order to get a homogenous mixture, the SiCNWs are ultrasonically diffused in ethanol for 10 min before vibration-mixing with the Al powder for 30 min. The mixture is dried at 120°C and sieved into a fine powder. The prepared composite powder is hot pressed at 600°C under pressure of 40MPa for 1hr in argon gas. It is indicated that the density of the composite specimens is higher than that of the monolithic SiCNWs and monolithic Al means SiCNWs are well distributed within the Al matrix. Due to the addition of the SiCNWs, the wear performance of metal based material is significantly enhanced as composites with 15% vol of SiCNWs show 76.95% decrease in wear rate compared to pure Al [13].

Many studies on Al-CNT have been performed using the PM method. A study has accounted a 350% enhance in the compressive yield strength with 1.6vol% CNT addition, owing to a homogeneous distribution of CNTs achieved by the nanoscale dispersion method. The homogeneous distribution and good interfacial bonding of CNTs increase strength directly on Al powder through the chemical vapour deposition (CVD) method before compacting and sintering. With the addition of 6.5vol.-% CNT, they have also achieved an increase in hardness tensile strength. Al powder (99.9% pure) and MWCNTs (formed by the spray pyrolysis method) were mixed in an ultrasonic bath for 5 min and milled in a high-energy shaker mill and the milling media to powder weight ratio was 5:1. There is no addition of PCA and argon gas applied while all milling runs are being performed. Consolidated products are done with the applied pressure of 950 MPa and 2 min holding time. Compacted specimens are pressure-less sintered during 3hrs at 823K inside vacuum (2Torr). As a result, the relative densities of the nanocomposites are 1–5% lower than the theoretical values. Furthermore, the σ_{max} increased as the milling time and MWCNT concentration increased. The nanocomposite prepared with 2hrs of milling time and 0.75wt.% MWCNT reached the maximum value of around 77Hv, compared with the shorter milling time (1hr), which has the most significant strengthening effect on the nanocomposites—the effect of nanocrystalline state [9].

Al (particle size smaller than 63µm) and Al_2O_3 (a-alumina powder with 99.5% pure, average size of about 27-43nm) nanocomposites have undergone high-energy planetary ball mill and are then fabricated under 420 MPa pressure with holding time of 5 min. For sintering, the compressed powder are kept at 624-626°C for 45 min under argon gas atmosphere and then the samples are furnace cooled. This study revealed that the agglomerations of particles would be removed by increasing milling time. At 4hrs milling time, Al_2O_3 agglomerations are yet to be observed, but are smaller and less than the no milled powder. However, a uniform distribution of the reinforcement particles can be caused by increasing the milling time, dissolution of particles agglomerations and reduction of distances between them. It can be noted that, this milling time particles have been under deformation and cold welding, therefore, flattened particles with high aspect ratios are formed. This is because Al particles are soft and their sizes are increased by cold welding. High sintering temperature (625°C) and differences in thermal expansion coefficients of Al and Al_2O_3 produced thermal stress. This stress will disappear by dislocation production that causes an increase in dislocation density means—important for strength enhancement. Agglomeration of Al_2O_3 particles cause stress concentration and unexpected fracture thus strength is increased by uniform distribution of Al_2O_3 particles [16].

In a recent study, pure Al powder (minimum of 99.7% pure, average size between 10 and 100µm) and reforcing agent of SiC (average size of 200nm) and Al_2O_3 (average size of 60nm) ceramic nanoparticulates are used. Several Al-based nanocomposites containing up to 5vol.% of SiC and Al_2O_3 nanoparticulates have been prepared using conventional PM route. Both Al powder and nanoparticulates in addition to 0.5-1.5wt.% paraffin lubricant wax are placed mechanically and mixed until a homogeneous mixture is achieved. The powder is cold compacted under 500MPa pressure. The compacted powder is sintered under argon inert gas atmosphere at 600°C for 100 min. After sintering, the nanocomposites are subjected to hot extrusion at 500°C using an extrusion die. As a result, when the volume fraction of the nanoparticulates dispersed into the Al matrix is increased, the agglomeration percent of the nanoparticulates also tends to increase and is found to be concentrated on the grain boundaries of the Al grains. Furthermore, it has been found that the Al/ Al_2O_3 nanocomposites exhibited better nanoparticulates distribution than Al/SiC nanocomposites. The Al/SiC nanocomposites exhibited more agglomeration percent and the agglomeration size varied between 0.5 and 10µm in size. Although small agglomerates in Al/SiC and Al/ Al_2O_3 nanocomposites still existed in the matrix, the agglomerates have been greatly improved when compared with the severe agglomerates in the nanocomposites fabricated using traditional mechanical stirring method [17].

Another study conducted on CNT is the dispersion in a solvent; after which it is sonicated for 20 min and followed by evaporation by heating the solvent. Al and the reinforcement of CNT, GR are blended in ball milling furnace for 10 min at 200rpm, which is essential for uniformity of the product. Samples were compacted under load of 135KN for 2 min. For sintering, the green compacts are heated up from room temperature to 660.32°C for 45 min under nitrogen atmosphere to avoid surface contamination.

Shrinkage of AL+CNT+GR and AL+CNT+GR+ND is not favorable during sintering and results in pore size reduction. The density values of AL+CNT+GR+ND composition are very near to the density value of base metal while the density values of AL+CNT+GR composition are less compared to the density values of AL+CNT+GR+ND composition. For AL+CNT+GR+ND composition, the hardness values are higher compared to AL+CNT+GR composition. The wear resistance increases with the amount of reinforcements as comparison between AL+CNT+GR and AL+CNT+GR+ND composition shows wear resistance difference as high as 2% [12].

3.1.3 Cold Pressing

Al powder (99.98% pure, 25μm), Si powder (98.5% pure, 25μm) and two types of nanoparticles of γ-Al_2O_3 (99.98% pure, 50nm) and rutile-TiO_2 (99.8% pure, 30nm) are prepared. Dry mixing method is used to mix the powder of alloy (Al-12%Si) with both Al_2O_3 and TiO_2 or with single Al_2O_3 or TiO_2. The mixing time was for 4hrs at milling speed of 650 rpm to obtain good particles distribution. Cold compaction is carried out at 10Mpa pressure followed by sintering process at 520°C for 90min with argon flow rate 2L/min. As a result, the sample with 4wt% Al_2O_3 showed the highest hardness because of nano Al_2O_3 has higher hardness compared to TiO_2. It is proved that mechanical milling produces uniform dispersion of the reinforcement nanoparticles in the Al-12wt%Si matrix. The nanocomposites reinforced with single addition of 4wt% Al_2O_3 nanoparticles showed the highest hardness and higher wear resistance compared with the base alloy and other nanocomposites [6].

3.1.4 Hot Isostatic Pressing (HIP)

Al–graphene composite powders are fabricated by consolidation process via hot isostatic pressing (HIP). HIP is done at 375°C for 20 min. Samples of pure Al, 0.1wt% graphene and 1.0wt% MWNT are made. Due to the greater interfacial contact area, the dispersion of graphene is complicated when compared to CNTs thus a low weight fraction of graphene is selected. After HIP, the billets are preheated to 550°C for 4hrs and then extruded on a 50 tonne extrusion press. The presence of MWCNTs increases the tensile strength of Al of up to 12%. However, during processing, graphene tends to form aluminium carbide that leads to the decrease in hardness and tensile strength of Al. The formation of aluminium carbide is because of the nature of graphene—produced by thermal exfoliation/reduction of graphite [18].

3.1.5 Extrusion Process

Al alloy 6061/SiC nanocomposites are produced by PM using ball milling process followed by secondary forming process; extrusion. All the billets are extruded at 37°C and the extrusion ratio (ER) is 6:1 which produced 1.8 of true strain. Other studies that have analyzed the microstructure of the effect of extrusion temperature on Al alloy matrix composites concluded that after increasing the values of the extrusion temperature up to a certain point, the particles are much more uniformly distributed. If the temperature is not high enough, a homogeneous distribution of the particles will not occur as it failed to assist the flow of the matrix alloy under the applied stress. Furthermore, a partial melting of the matrix alloy at the grain boundaries happens if extrusions are carried out at a relatively high temperature that cause the particles to get suspended in the melt matrix near the grain boundaries. It has been reported that the number of pores decreased effectively and the interfacial bonding strength between the matrix and reinforcement particles is improved by the extrusion method [4].

3.2 Liquid-state Processes

3.2.1 Stir Casting Method

A356 alloy reinforced with MgO nanoparticles have been fabricated via stir casting method. Density measurements of fabricated samples have revealed that the bulk density of samples increases with the increase in vol.% of MgO up to 2.5% at 800, 850 and 950°C. However, the density for cast samples at 800 and 950°C decreased due to the pores formation and agglomeration at high content of reinforcement particles. In fact, the incremental trend is dominant at 850°C for the bulk density. The values obtained for bulk densities of the nanocomposites are remarkably close to the corresponding theoretical density values. Figure 1 shows the XRD pattern of nanocomposite containing 2.5 vol% of MgO fabricated at 850°C. It can be concluded that the uniform presence of MgO in Al matrix with no signs of formation of other intermetallic phases has been approved by the XRD phase analysis. Furthermore, the reinforcement particles are uniformly distributed in the matrix alloy, in spite of regional agglomerations [19].

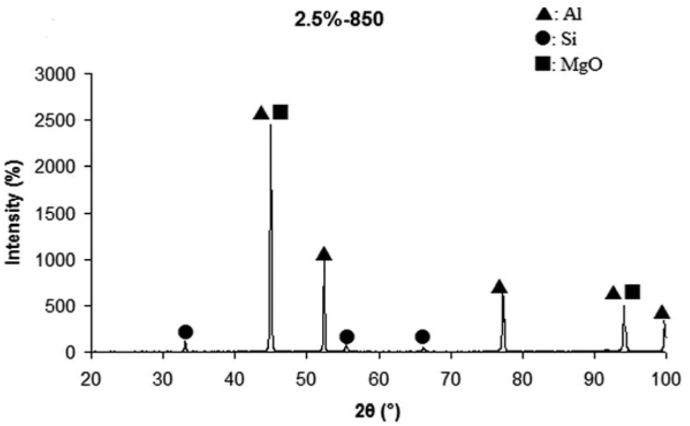

Figure 1 XRD pattern of Al-2.5% MgO nanocomposite casted at 850 °C [19]

The stir casting technique is performed to fabricate Al (99.7% pure) and nano-sized Ilmenite ($FeTiO_3$) particulate composites. As a result, the Ilmenite particles that are evenly distributed through some of the clusters are formed; nevertheless good distribution of particles is achieved. As the reinforcement is increased, the tensile and hardness values are also increased. It can be observed that 5wt% nano Ilmenite reinforcement exhibits maximum tensile strength and hardness values and it can be concluded that the mechanical properties, both hardness and tensile strength have been increased, compared to the cast Al that maintained the ductility nature of the matrix material [20].

A study has been conducted on Al alloy reinforced with nano-ZrO_2 particulates dispersed by Disintergrated Melt Deposition (DMD) technique followed by hot extrusion. Al alloy is heated up to 720°C and the preheated (200°C) reinforcement is added. To get a uniform distribution of the reinforcement, Al alloy and preheated reinforcement are well stirred at 450 rpm by a vortexer. In secondary processing, extrusion of the deposited monolithic and nanosized ZrO_2 containing Al matrix is conducted in a hydraulic press at 250°C. Microstructural analysis showed fairly uniform distribution of reinforcements in fine grain refinement with the least porosity formation. As reinforcement content is increased up to 12%, improvements are seen in the mechanical properties as well as fracture toughness due to the increasing trend in the matrix hardness. A higher constraint to the localized deformation during indentation is due to the presence of ZrO_2 and reduced grain size [21].

3.2.2 *Ultrasonic Cavation Method*

Boron carbide, B_4C (size 50 nm) particulates are used as its density is close to the Al and thus the particulate will not tend to agglomerate during the process. AA2024 Al alloy is heated up to 638°C as well as the sonication process. B_4C particles are added at various weight percentages to the melt during the cavitation process in argon atmosphere during melting. The metal is poured into a die and plates are cast. The as cast plates are heat treated (solutionised at 560°C for 1hr) and ageing is done at 160°C for 12 hrs. The heat treated plates underwent a rolling process to remove the casting defects as well as for grain elongations. The hardness, ultimate tensile strength and yield strength of the nanocomposites have been improved significantly by the presence of B_4C_p particles, which is increased by 14%, 6%, 11%, accordingly [22].

3.3 Semi-solid Processes

For this process, only a few works are available including the combination of rheocasting followed by squeeze casting while the other is a semi-solid route stir casting, even if this method has been applied widely in fabrication of the conventional method.

3.3.1 *Combination of Rheocasting and Squeeze Casting Method*

The A356 alloy/Al_2O_3 nanoparticles are prepared using a rheocasting technique followed by squeeze casting techniques. A356 alloy is melted at 680°C and allowed to cool to semi-solid temperature of 602°C as the liquid/solid fraction is about 0.7 whereby the stirring started at approximately 1000 rpm. Before stirring, Al_2O_3 nanoparticles are preheated up to 400°C for 2hrs and added while stirring, which formed a vortex. After that, during the agitation, preheated Al_2O_3 are mixed into the matrix. The agitation stopped after completing the addition of Al_2O_3 nanoparticles. Then, the molten mixture is poured into a preheated tool steel mould and immediately squeezed during solidification using a hydraulic press of 50 tonne-capacity for 5 min. The nanocomposites are then heat treated at 540°C for 3hrs and then quenched in cold water. After cooling, the nanocomposite samples are artificially aged at 160°C for 12hrs. As a result, the A356/ Al_2O_3 containing up to 3% of 60nm Al_2O_3 nanoparticles showed better thermal conductivities than A356/

Al_2O_3 containing 200 nm nanoparticles. Compared with the A356 base alloy, the A356/ Al_2O_3 showed lower electrical conductivities as the nanoparticles are increased in volume fraction and size from 60 to 200nm [23].

3.3.2 Semi-solid Route Stir Casting Method

A sample of purified MWCNTs is mixed with pure Al powder (average size 100□m) with a weight ratio of 1:6 and stearic acid is then added as PCA. The MWCNTs are dispersed with the Al powder by ball milling at 200 rpm for 1hr and the mixture is then compacted at 90 MPa for 10 min. In order to improve the wettability of the matrix alloy, a 0.5% weight fraction of pure magnesium that serves as a surfactant is added to the melt. Stirring process is performed at 500 rpm for 1 min in semi-solid state (590-600°C) after the preinfiltration of the preform by the molten metal for 30 sec. Argon gas is purged to prevent hydrogen entrapment during the melt processing. The tensile strength increases from 155.4 MPa for the monolithic alloy to an average value of 201.2 MPa for 1.5wt% MWCNTs reinforced composite of which the maximum value is 208 MPa. The increase in the tensile strength due to the increase of the dislocation density in the matrix around the MWCNTs results in thermal expansion mismatch between the MWCNTs and the matrix [24].

A356 Al alloy was melted at 660°C and then allowed to cool to semisolid temperature of 601°C and a 0.75% weight fraction pure Mg is added to the melt to improve the wettability. Al/MWCNTs blocks or billets introduced into the melt and stirring continued for 1 min in semi-solid state after which the preinfiltration of the preform by the molten metal for another 1min to produce homogenous mixture at slurry temperature of 620°C. The agitation was stopped after completing the addition of Al/MWCNTs billets or blocks and the molten mixture was poured into a preheated low carbon steel mould (250°C) and immediately squeezed during solidification. The pouring temperature for the process is 601°C, and the speed of impeller is 750 rpm. Well and uniformly dispersed MWCNTs into the melt alloy, resulted in good distribution and less agglomeration, which improved the mechanical properties of the castings. During cooling to room temperature and the difference of the coefficients of thermal expansion (CTE) between the matrix and CNTs, MWCNTs help in strengthening and hardening the matrix by increasing the matrix alloy dislocation density. This behaviour may also be partly attributed to the grain refinement that is accompanied with the addition of MWCNTs and stirring action. Due to grain refinement and effects of the strengthening of nanoparticles, the weight fraction of MWCNTs increases as the hardness increased [25]. The A356 matrix alloy reinforced with 1.5wt% MWCNTs revealed the ultimate tensile and yield strength properties and elongation percentage due to the uniformly distributed of reinforcement and grain refinement of Al matrix and the elongation percentage. The compressive strengths of nanocomposites have been increased with increasing MWCNTs weight fraction compared to A356 Al alloy at optimal value of 1.0wt%. Large amounts of CNTs have poorly affected the material strength due to cluster formation of the particles or poor wettability with the matrix [26].

4.0 CONCLUSION

This paper presents a review on various techniques applied for the fabrication of AlMNCs. The techniques include high energy ball milling, PM route that includes compaction process such as cold compaction followed by sintering, HIP and extrusion, stir casting, ultrasonic cavation, combination of rheocasting and squeeze casting and semi-solid route stir casting method. The challenges on the fabrication of AlMNCs are such as low wettability of molten metal. It can be concluded that PM is the most suitable method for the manufacturing of AlMNCs. In order to achieve improvement in the mechanical properties, it is believed that sintering process could be followed by a secondary machining and finishing by a PM route and should be further explored.

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