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ALUMINUM METAL MATRIX NANO COMPOSITES (AL MMNCS) – MANUFACTURING METHODS: A REVIEW

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ABSTRACT

Applications of Aluminum alloy structural components are many in automobiles, aircrafts and many other defense systems due to their enhanced properties and strength to weight ratios. The mechanical tribological and other properties of Aluminum alloys would be increased considerably if reinforced by nano ceramic particles such as SiN, SiC, SiO_2, and Al_2O_3 etc. However, it is very challenging to disperse the nano ceramic particles uniformly in the various aluminum alloy melts for solidification process of bulk Aluminum metal matrix nano composites(Al MMNCs). There are several methods mentioned in the literature for fabrication of Al MMNCs such as solid state, liquid state and deposition process. Various researchers have tried various methods including powder metallurgy, stir casting, in situ and other methods and every method has its advantages and limitations and achieving uniform distribution of reinforcements with nano ceramic particles in Al alloy melts is the whole some objective. A thorough review of various methods and proposals published during last 15 years for manufacturing of Al MMNCs. for enhanced properties –comparisons were presented.

KEYWORDS: Aluminum, Metal Matrix Nanocomposites (Al Mmncs), Ultrasonic Cavitation, Nanoparticle Dispersion, Solidification Processing

1. INTRODUCTION

Metal matrix composites (MMCs) reinforced with nano-particles, also called Metal Matrix nano-Composites (MMNCs), and are being investigated worldwide in recent years, owing to their promising properties suitable for a large number of functional and structural applications. The reduced size of the reinforcement phase down to the nano-scale is such that interaction of particles with dislocations becomes of significant importance and, when added to other strengthening effects typically found in conventional MMCs, results in a remarkable improvement of mechanical properties [1–4].

Processing of Aluminum Metal Matrix Nano Composites

The major challenging in processing of composite materials is to get defect free microstructure and homogeneously distribution of reinforcements. Based on the shape, the reinforcing phases in the composite can be either particles or fibers. The relatively low material cost and suitability for automatic processing has made the particulate-reinforced composite preferable to the fiber-reinforced composite for automotive applications. Primary processes for manufacturing of AMCs at industrial scale can be classified into two main groups. (A). Liquid state processes: Liquid state processes include stir casting, compo casting, and squeeze casting spray casting and *in situ* (reactive) processing, ultrasonic assisted casting. (B). Solid state processes: Solid state process include Powder blending followed by consolidation (PM processing), high energy ball milling, friction Stir Process, diffusion bonding and vapor deposition techniques. The selection of the processing route depends on many factors including type and level of reinforcement loading and the degree of micro structural integrity desired.

For the large-scale production of metal matrix nanocomposites, the main problem to face is the low wettability of ceramic nano-particles, which does not allow the preparation of MMNCs by conventional casting processes since the result would be an inhomogeneous distribution of particles within the matrix. The high surface energy leads to the formation of clusters of nanoparticles, which are not effective in hindering the movement of dislocations and can hardy generate a physical-chemical bond to the matrix, thus reducing significantly the strengthening capability of nanoparticles. Several unconventional production methods have been studied by researchers in order to overcome the wettability issue, either by formation of the reinforcement by *liquid state process* or by *solid state process* addition of the ceramic reinforcement by specific techniques. Hereafter, the most studied and successful methods are described by classifying them into liquid, semisolid and solid processes.

The methods used for the characterization of MMNCs are the same of those used for conventional MMCs and alloys. Of course, the downsizing of the reinforcement implies the use of higher resolution techniques for characterization of morphology and local chemistry of the constituents. In the literature, different kinds of matrix metals have been coupled with several types of nano metric phases. Ceramic compounds (SiC, Al2O3, *etc.*), inter metallic materials and carbon allotropes were used to reinforce Al, Mg, Cu and other metals and alloys. Particular importance is assigned to carbon nanotubes (CNT), which are characterized by very high strength, stiffness and electrical conductivity. These properties confer higher mechanical strength while improving electrical and thermal properties of the base material. Moreover, MMNCs revealed to be able to improve other interesting engineering properties, such as damping capacity, wear resistance and creep behaviour [5-9].

This paper is aimed at thorough review of various methods and proposals published during last 15 years for manufacturing of Al MMNCs. for enhanced properties –comparisons were presented.

2. VARIOUS MANUFACTURING METHODS FOR PREPARING AL MMNCS DURING LAST FEW YEARS

1.1 Stir Casting

Metal matrix composites were made by using stir casting process in the year 1968 [10]. S. Ray et.al introduced alumina particles into aluminum alloy melt containing ceramic powders by stirring [10]. The resultant molten aluminum alloy, with ceramic particles, can be used for sand casting, die casting. Stir casting process is suitable for manufacturing composites with volume fractions ≤ 30% of reinforcement [11]. In this process mechanical stirring in the furnace is the key element. The casted composites can be extruded for to reduce porosity; it improves bonding, to refine the microstructure, homogenize the distribution of reinforcement and which leads to break-up of particle agglomerates [12]. Schematic of stir casting design setup shown in figure 2.1.

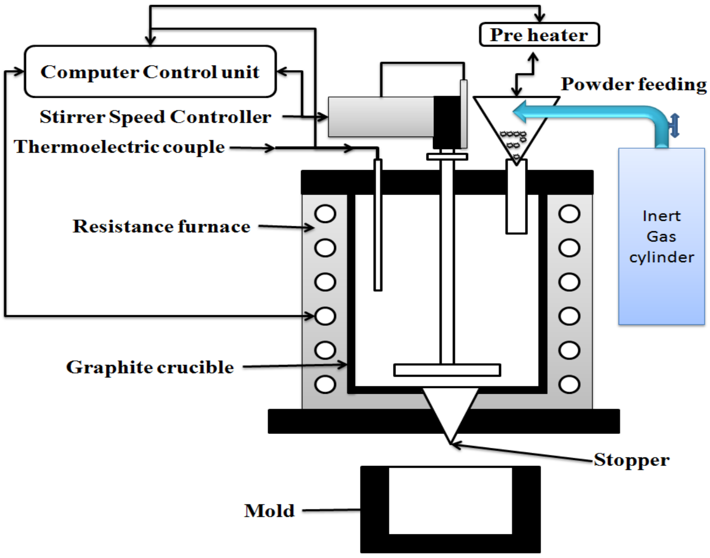

Figure 2 1: Schematic of Stir Casting Design Setup

There are some advantages compared to other routes by melt stirring process, simple, applicability to large production quantity, its flexibility, better matrix reinforcement bonding, and excellent productivity for near net shaped components [13]. The major problem associated with stir casting of Aluminum MMNCs such as heterogeneous distribution of the reinforcement material, and poor wettability. When the reinforcement particles are added to the molten metal matrix, they float on to the melt surface. Due to the surface tension, very large specific surface area, high interfacial energy of reinforcement particles, presence of gas layer on the ceramic particle surface and oxide films on the melt surface. In this process mechanical stirring can be applied for to mix the particles into the melt, when stirring stops, the particles tend to back to the surface [14]. By giving heat treatment to the reinforcement particles before dispersion into melt can be improved the wettability of reinforcement particles within the molten matrix alloy and the adsorbed gases can be removed from the particle surface [15]. Another problem is if the reinforcement particles are distributed uniformly in molten matrix, they tend to sink or float to the molten melt due to the density differences between the reinforcement particles and the matrix alloy melt. If the dispersion of reinforcement particles is not uniform then they have high tendency to agglomeration and clustering. By injecting the particles with an inert gas into the melt is useful in improving the distribution of the reinforcement particles [16]. When the reinforcement particle size reduce to nano scales then wettability and distribution of reinforcement particles become more difficult due to increasing of surface energy and surface area of nano particles, and cause an increasing tendency for agglomeration of reinforcement particles. The flow chart of stir casting process is shown in figure 2.1.1.

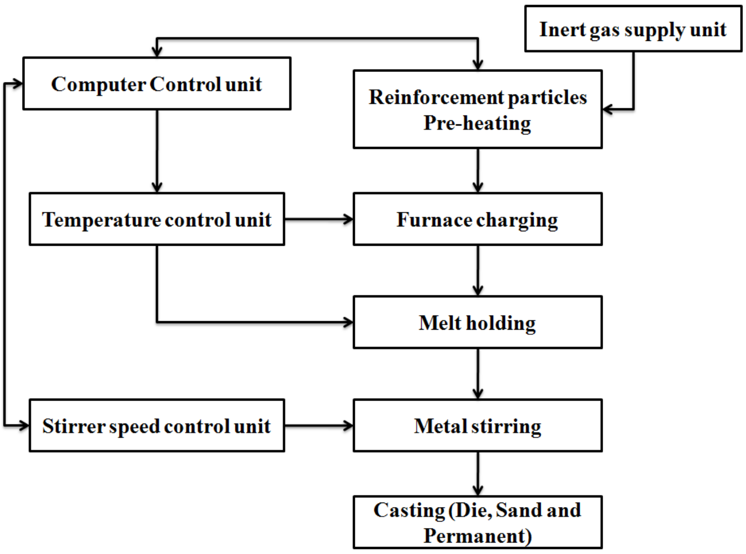

Figure 2.1.1: Flow Chart of Stir Casting Process

Several structural defects such as particle clusters, porosity, oxide inclusions and arise from casting technology [17]. Three step mixing method can be improved the wettability, agglomeration, separation of particles and distribution of nano-sized reinforcement particles, with addition of mechanical stirring, ultrasonic stirring and centrifugal force stirring [15, 18]. The stir casting method is most economical and well-established metal matrix composite fabrication method [18].

2.2. Compo Casting

Stir casting is the one of the simplest method for producing aluminum matrix composites. However, it results poor incorporation and distribution of the reinforcement particles in the matrix. As the reinforcement particle size decreases there is a tendency of formation of agglomeration and reduced wettability with the melt. Development of new techniques for addition of very fine particles to metallic melts which would result in more uniform distribution and effective incorporation of the reinforcement particles into the matrix alloy. Therefore we move towards Compo casting. Compo-casting involves incorporation of particulate reinforcements in the semisolid metal matrix using mechanical mixing [19]. Good distribution of reinforcements in the metal matrix and weak agglomeration of particles have been achieved through compo casting [20]. Because of lower operating temperatures than when using liquid metal matrices energy can be saved by compo casting and longer tool life [21]. The Compo casting is shown in figure 2.2.

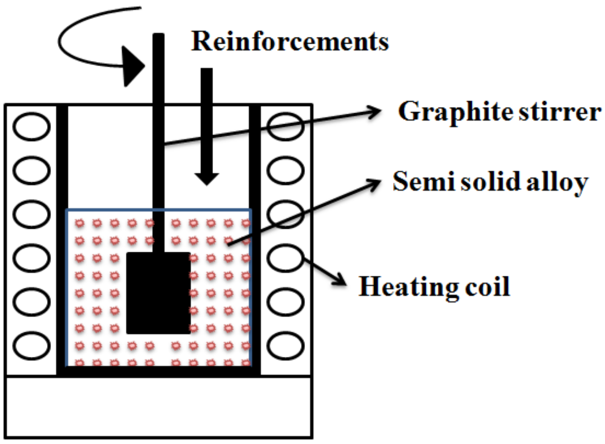

Figure 2.2: Design Setup of Compo Casting

Compo-casting method the particles are incorporated at semi-solid temperature of the alloy [22]. Chemical reaction between molten aluminum and silicon carbide will not occur, due to the low relative operating temperature, the formation of Al_4C_3 chemical compound can be avoided via compo-casting [23]. The melting process has two major problems, one is ceramic particles are not wetted by the liquid metal matrix and secondly, the particles tend to float according to their density relative to the liquid metal, the dispersion of ceramic particles are not uniform. To decrease the porosity in the composite material, the squeeze casting and die casting methods is needed [24]. Ductility of compo-casting was greater than stir casting samples with decreasing of particle size and particle percent [22].

2.3 Squeeze Casting

The concept of squeeze casting dates back to the 1800s [25]. The idea was suggested by Chernov in 1878 [27] to apply steam pressure to molten metal while being solidified. Squeeze casting experiment was not conducted until 1931 [26]. Squeeze casting process is the combination of closed die forging and gravity die casting. The technique in which metal solidifies under pressure within closed die halves. Squeeze casting operation has been referred to as pressure crystallization [28], liquid pressing [29], squeeze forming [30], and extrusion casting [31]. Squeeze casting fabricated components have superior weldability and heat treatability [32]. Squeeze casting process shown in figure 2.3.

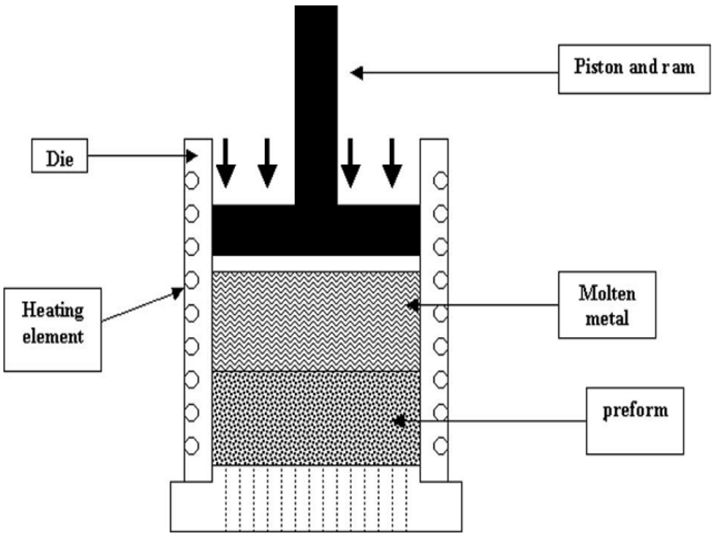

Figure 2.3: Schematic Diagram of the Squeeze Casting Apparatus [33]

The squeeze casting of aluminum alloys can fulfill wide range of requirements in a special way, when compared to other production methods and materials. Squeeze castings basically divided into two types: direct and indirect, where the squeeze pressure is applied through the die-closing punch itself, where as in indirect process, the squeeze pressure is applied after closing die, by a secondary ram. From this process no shrinkage porosity, near net shape, high degree of surface finish and dimensional accuracy.

2.4 Powder Metallurgy

The non-conventional methods have been proposed, to overcome the problems like formation of clusters and low wettability and the high surface area to volume ratio of ceramic compounds during preparation process of MMNCs. Powder metallurgy processing method as shown in figure 2.4

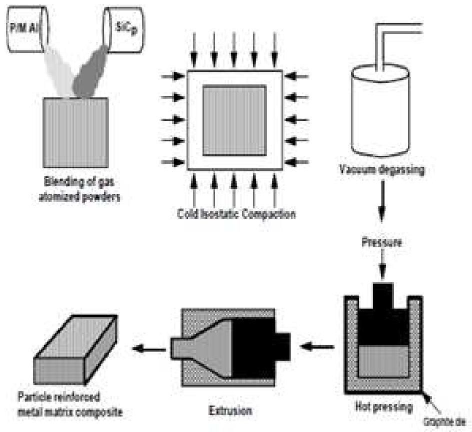

Figure 2.4: Schematic of Processing of Powder Metallurgy [38]

The powder metallurgy routes one of the promising non conventional method [34].

Powder metallurgy route can exploit the nano particles and grain boundaries strengthening capability [35]. Powder metallurgy processes the process temperature is lower and make the inter phase kinetics precisely controlled. There are traditional stages of Powder Metallurgy-AMMNCs fabrication including mixing and blending the powders; degassing the solidified product in vacuum; homogenizing through hot isostatic pressing [36]. Aluminum metal matrix composites with ceramic particles are relatively easy to process are nearly isotropic in comparison with fiber reinforced composites [37]. The Powder metallurgy process is a unique part fabrication method that is highly cost effective in producing complex parts at very close dimensional tolerances, with minimum scrap loss and fewer secondary machining operations. However, this method requires alloy powders that are generally more expensive than bulk material, and involves complicated processes during the material fabrication. Thus, powder metallurgy may not be an ideal processing technique for mass production.

2.5 High Energy Ball Milling

High energy ball milling as a powder processing method involves repeated deformation, welding and fracturing of powder particles. In this method starting powder particles are trapped between highly kinetic colliding balls and inner surface of the vial, it causes repeated deformation, re-welding, fragmentation of premixed powders resulting in forming dispersed particles in grain refined matrix [46]. It is widely used technique to synthesize composites with the addition of ceramic hard particles to metal alloys increase the strength, wear resistance and micro hardness during high energy ball milling [39]. High energy ball milling extensively employed to obtain extended solid solutions [42], amorphous structures [43], nanocrystalline solids [44], metasatable phases [45] and immiscible components [46]. The sintering temperature can be reduced to the increased bulk and surface energies introduced during the milling process [41]. The method is not suitable for mass production; maintenance is difficult because of the powder can be milled by providing inert atmosphere. It is time taking process for to reach required properties of composites.

2.6 In Situ Synthesis

Aluminum matrix composites are reinforced with various ceramic particles such as SiC [47, 48]; AlN and TiC [49] are fabricated through squeeze casting, stir casting and powder metallurgy. However, these fabrication processes usually require expensive reinforcement materials and involve complex equipment and procedures, thus imposing relatively high cost. An alternative route for cost effective fabrication of metal matrix composites is in situ method developed in recent years with various reinforcement ceramic particles SiC [50], AlN [51] and TiC [52]. It offers a number of attractive features, such as good reinforcement/ matrix compatibility, homogeneous distribution of the reinforcing particles, and potentially low cost. In this method one of the reacting elements is usually a constituent of the molten matrix alloy. The other reacting elements may be either externally added fine powders or gaseous phases. In situ process as shown in figure 2.6

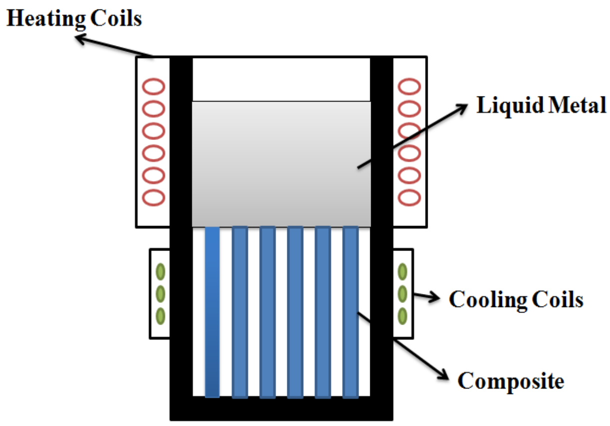

Figure 2.6: Process of in Situ Synthesis

The preheated ceramic particles are injected into the molten aluminum; it is difficult to disperse the reinforcing particles uniformly in metal melts due to the low wettability with the melt [53]. The interface bonding may be lowered due to the porosity and segregation at the interface between the matrix and reinforcement [54]. It requires the higher reaction time temperature and longer holding time, which is greatly, increases the cost of production.

2.7 Pressure Less Infiltration

Pressure-less infiltration technique is a cost effective method compared with common processes of powder metallurgy and casting in manufacturing of metal matrix composites containing high volume fraction of reinforcements [55]. The creep behavior can be improved [56]. The major problems can be encountered in the processing by pressure-less infiltration technique, better wettability and the presence of unwanted reaction products Al_4C_3 between Al and SiC [57]. Pressure-less infiltration method is successful, where loose powder beds and performs of various ceramic materials by molten aluminum alloys has been reported over the past decade [58].

2.8 Ultrasonic Assisted Casting

In scientific literature Ultrasonic’s in materials processing has shown vast capability and potential [59]. During solidification ultrasonic vibrations method produces in finer grain size in cast products [60]. In this process main improvement in convection and induces cavitations during solidification, it leads to various physical and indirect chemical effects in the liquid [61]. Design of ultrasonic assisted casting process as shown in figure 2.8.

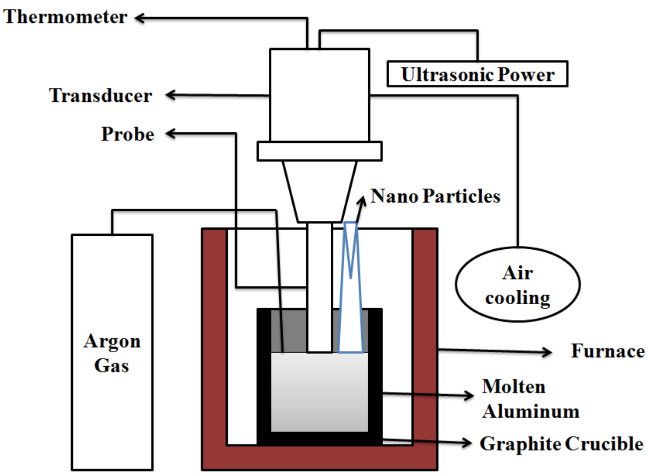

Figure 2.8: Design of Ultrasonic Assisted Casting Process

Traditional fabrication processes, such as high energy ball milling, electroplating, rapid solidification and sputtering etc, cannot be used for mass production. Mechanical stirring can provide only for breaking up large clusters provide shear stress larger enough to break up smaller clusters of particles [61]. In the melt there is a tendency of small particles to aggregate together to decrease the free energy of the whole system and clusters may form in the metal matrix nano composites [62]. The oxide inclusions can be entering into the melt during mechanical stirring; gases are inevitably entrained in the oxide inclusions, which can form the porosity in the metal after solidification [63]. Ultrasonic assisted casting process the strong impact coupling with local high temperatures can potentially break the nanoparticle clusters and clean the particle surface. A356 alloy reinforced by SiC nanoparticles have been fabricated by using ultrasonic cavitation method [64]. There are advantages such as matrix-reinforcement bonding, low cost processing and nearer net shape can get form ultrasonic stir casting method [65].

2.9 Friction Stir Welding (FSW)

Nano reinforcements in a uniform are critical and difficult task. All existing processing techniques for forming surface composites are based on liquid phase processing at high temperatures. It is hard to avoid the interfacial reaction between reinforcement and metal matrix and the formation of detrimental phases. The problems can be avoided by considering critical control of processing parameters to get ideal solidified microstructure in surface layer; by carrying at temperatures below melting point of substrate. At present, much attention has been paid to a new surface modification technique i.e., Friction stir processing. Friction stir processing has widely been investigated, an outgrowth of friction stir welding, has been employed to produce composite layers on surface by using nano, micro and macro sized reinforcements [66]. Friction stir processing has been carried out on Aluminum 7075 using nano sized SiC reinforcements, which were shown good metallurgical and mechanical properties such as strength, stress corrosion crack resistance and excellent fatigue resistance [67]. The reinforcement particle size and as well as shift of rotational direction between passes effected on the microstructure and mechanical properties of the material have been addressed in literature [68]. In this process there is non- consumable rotating tool and the work piece to raise the local temperature of the material to the range where it can be plastically deformed easily. The rotating tool traverses along the joint line, metal is essentially extruded around the tool before being forged by the large down pressure. The stirred zone consists of fine and equiaxed grains produced due to dynamic recrystallization.

2.10 The Spark Plasma Sintering Process

In this process the heating is accomplished by spark discharges in voids between the particles, generated by an instantaneous pulsed direct current which is applied through electrodes at the top and bottom punches of the graphite die, due to this the particle surface activated, purified and self heating phenomenon is generated between the particles [69]. Spark plasma sintering process is a novel method for the manufacture of fully dense materials [70]. Spark plasma sintering, has been successfully used in nanostructure powder consolidation [71]. Spark plasma sintering method is not only for to produce a dense bulk material within short processing duration, but also to fabricate nano-materials and to get special microstructures [72]. The conventional method of sintering renders poor adhesion, coarse micro structure, low strength, low hardness and density at higher temperatures [73].

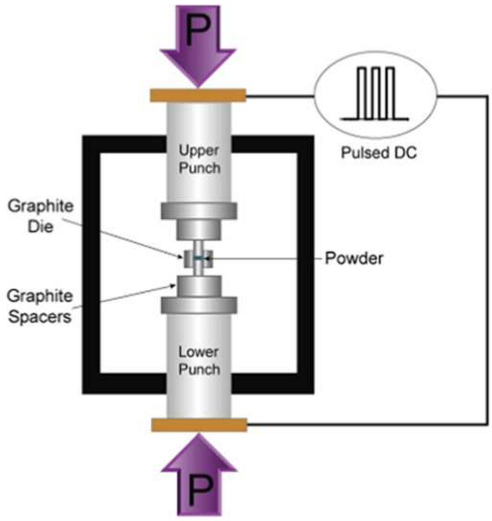

Figure 2.10: Schematic of the Spark Plasma Sintering Apparatus [76]

The spark plasma sintering technique is becoming more important because of getting enhanced material properties, effective interface formation, cleaner grain boundaries, and effective shrinkage at lower processing temperature and within a shorter sintering time to consolidate powders compared to conventional methods [74]. Combination of spark plasma sintering and hot extrusion processes demonstrated by authors the feasibility of making aluminum-carbon nano tube composite materials [75].

3. COMPARISONS OF VARIOUS MANUFACTURING METHODS

3.1 Stir Casting

In stir casting process, if the reinforcement particles size is in nano then there is a tendency to form greater agglomeration and with poor wettability of the particles with the melt. Stir casting, it suffers from poor incorporation and distribution of reinforcement particles in the matrix. A. Sakthivel et al study, 2618 aluminum alloy metal matrix composites reinforced with different sizes of SiC_p particles, with increase of weight fraction of reinforcements, there is a tendency of porosity formation. The mechanical properties such as hardness, tensile strength and hot tensile strength (at 1200ºC) and impact strength were improved with decrease of reinforcement particle sizes [77]. Through Stir casting method large production rates are possible, it is low cost technique and nearer net shape castings can be reached [78]. The long stir time gives uniform particle distribution but it results in too much gas and oxidation to Al matrix. Ultrasonic treatment is very effective to reduce stir time, gas and oxidation as well as dispersing particles [79].

3.2 Compocasting

In Compocasting process porosity is lower than the stir casting process and better wettability between the matrix and reinforcement particles as well as the lower volume shrinkage of the matrix alloy. The dispersion of the ceramic particles is not uniform and still porosity is presented to decrease the porosity in the composite material, the squeeze casting and die casting methods is needed [80]. If the particle size in nano range then enhances the wettability in between the molten matrix alloy and reinforcements and improves the distribution of the reinforcement particles in the solidified matrix [81]. It also increases the impact energy and the hardness of the composites and decreases their porosity.

3.3 Squeeze Casting

Squeeze casting method improves the mechanical properties of Al-MMNCs. This method produces castings very few defects and no porosity [82]. Squeeze cast products can be sued in as cast condition in engineering applications requiring high quality parts, while chill castings and sand castings may be used in as cast condition for non engineering applications or engineering applications with less quality [83].

3.4 Powder Metallurgy

To refine the microstructure and obtain homogeneous dispersion of ceramic reinforcements in the metal matrix is notated by mechanical milling process as part of powder metallurgy technique [84]. The parameters like volume fraction, green density, milling time, compact pressure, sintered density and hardness can effect on metal matrix composite [85]. Powder metallurgy process can prevent the formation of clusters, and homogeneously dispersed [86].

3.5 High Energy Ball Milling

High energy ball milling utilizes high energy impacts, high frequency from balls to repeatedly forge powder particles together [87]. In mixtures of ductile components the particles are initially flattened. The brittle component undergoes size reduction by fragmentation [88]. This process is time taking process to form metal matrix nano composites. Sometimes protective atmosphere require preventing the reinforcement particles, for the formation of oxides in the composite. Throughout put is less, so that not suitable for mass production of composites.

3.6 In situ Synthesis

Al MMNCs are fabricated through stir casting, squeeze casting and powder metallurgy; however theses fabrication methods require expensive reinforcement materials and involve complex equipment and procedures, relatively high cost. In situ process offers features, such as good reinforcement matrix compatibility, homogeneous distribution of the reinforcing particles, and low cost.

Pressure less infiltration

In this process the liquid metal flows in to the voids in the porous body without any external pressure [89]. It can provide good wettability, suitable for mass production. These liquid metal infiltration techniques are usually assisted with the use of an externally applied pressure (connected to very high vacuum), more expensive.

3.7 Ultrasonic Assisted Casting

Extremely difficult for the mechanical stirring method to distribute and disperse nano scale particles uniformly in metal melts due to their large surface to volume ratio and their low wettability in metal melts. By utilizing this method A356 alloy reinforced by SiC nanoparticles have been fabricated successfully [90]. Ultrasonic stirring has been used in the purifying, degassing and refinement of metallic melt.

3.8 Friction Stir Welding

On surfaces to get nano reinforcements in a uniform manner is a critical issue. Friction stir process is a solid state processing technique to obtain a fine grained microstructure. Though Friction stir process has been basically advanced as a grain refinement technique, it is very attractive process for also fabricating composites. This method is used for only surface modification to produce composites with good mechanical properties and corrosive resistance with the addition of nano, micro and macro size reinforcements [91].

3.9 Spark Plasma Sintering Process

Spark plasma sintering produces high heating rates, short sintering cycles, and low sintering temperatures that allow sintering nanostructure materials. The spark plasma sintering process has been shown to be an effective technique for consolidating metallic materials including nanocomposites. This method improves mechanical properties with good densification. It has been reported that the high performance metal matrix composites can be fabricated by using mechanical alloying process to mix the powders, and followed by rapid spark plasma sintering [92].

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