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2 Manufacturing of aluminium composite materials: A review

Abstract: Aluminium composite materials are becoming very popular as a result of their physical and mechanical characteristics, which are making them relevant to various applications. The addition of reinforcement materials with unique characteristics into aluminium produces aluminium composites with superior quality. Wear resistance, stiffness, strength and hardness are some of the improved properties obtained when reinforcement materials were added to the primary aluminium. This chapter presents some of the manufacturing processes of aluminium, its alloys and composites. The effects of reinforcements on aluminium composites from existing work and research direction on the fabrication of aluminium composite materials were discussed in this chapter.

Keywords: Composite materials, Functionally graded materials (FGMs), Manufacturing processes, Aluminium matrix, Powder metallurgy

2.1 Introduction

Aluminium comprises about 8% of the Earth crust, which makes it the second most plentiful element on the Earth's crust and it is never found in its pure state [1]. It is mostly available in its oxide form as micas, feldspars and clay. Aluminium is a light metal with a melting point of 658 °C, specific gravity of 2.7 and tensile strength between 90 and 150 MPa [2]. Aluminium, which was discovered in 1807, becomes widely commercialized after the invention of the Hall–Heroult production process in 1886 [3]. This history is summarized in Table 2.1.

Strengthening of aluminium is usually done by alloying using elements such as copper (Cu), magnesium (Mg), manganese (Mn), nickel (Ni), silicon (Si) and zinc (Zn) [4]. Addition of small amount of alloying elements changes soft and weak aluminium into a hard and strong metal and still retaining its light-weight property [2]. Some of the common types of aluminium alloys include duralumin with alloying elements composition of 3.5–4.5% Cu, 0.4–0.7% Mn and 0.4–0.7% Mg. Duralumin possesses maximum tensile strength and vastly employed in wrought conditions for stamping, forging, rivets, tubes, sheets and bars. Y-alloy is also known as copper-aluminium alloy, with alloying elements composition of 3.5–4.5% Cu, 1.2–1.7% Mn, 1.8–2.3% Ni, 0.6% Si, 0.6% Mg and 0.6% Fe. Addition of copper to pure aluminium leads to an alloy formation with better strength and Machinability properties, which enable it to be used in casting and forging purposes employed in applications such as aircraft engine piston and cylinder heads. Other types of aluminium alloys include

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Table 2.1: History of aluminium [3].

Year	Findings
1825	Danish chemist produced aluminium by reducing chloride with potassium amalgam.
1827–1845	German scientist Wohler determined essential properties after successfully separating small globules.
1854	French scientist Saint-Claire Deville reduced aluminium chloride with sodium.
1856	Deville started industrial production at Nanterre using sodium.
1886	Hall and Heroult independently developed the fused electrolysis method for producing aluminium from alumina dissolved in cryolite.
1888	Industrial production of aluminium by the new electrolytic method was started in America.
1910	Industrial production started in Switzerland at Neuhausen and in France at Froges. By 1910, production was established in seven countries (Canada, France, Italy, Norway, Switzerland, the UK and the USA); total output was 45,000 tonnes.
1918	By 1918, the total world production hit 208,000 tonnes from production in nine countries.

magnalium, which comprises about 2–10% Mg and 1.75% Cu added to melted aluminium, and hindalium, an alloy formed from aluminium and magnesium with little amount of chromium, Al-Bi, Al-Pb, Al-Si-Pb and Al-Sn alloy.

The application of aluminium is based on three main properties, such as its low density of about 2.7, high mechanical strength that can be achieved using appropriate alloying elements and heat treatments, and its high corrosion resistance ability [5]. Other properties of aluminium include its good reflectability, high ductility, heat and electrical conductance, low working cost and high scrap value. Aluminium and its alloys have wide range of application as they are highly employed in sheet because of its suitability with deferent fabrication methods. This allows them to be machined in deferent ways such as sawing, drilling and shearing, to be easily formed by bending, drawing and stamping, to be joined using processes such as bolting, soldering, brazing, adhesive bonding and welding, and to be finished using processes such as painting, plating, coating, polishing and patterning. The sheets are used in cooking utensils, railings, roofing, automobile structures, aircraft skin, beverage and food cans. Aluminium plates are employed in tank cars, military vehicles and tanks, aircraft structural parts among others. While aluminium foils are employed in food packaging, pharmaceuticals and so on, casting, forging, rolling, extruding, spinning, bending, drawing, shearing, powder metal forming and squeezing are some of the most common operations used for primary shaping processes [2].

Processing of aluminium and its alloys plays an important role in determining their properties. This is because properties of aluminium alloys greatly depend on their constituents and microstructure like grain size distribution, average grain size, precipitate volume fraction and crystallographic orientation aspects such as the

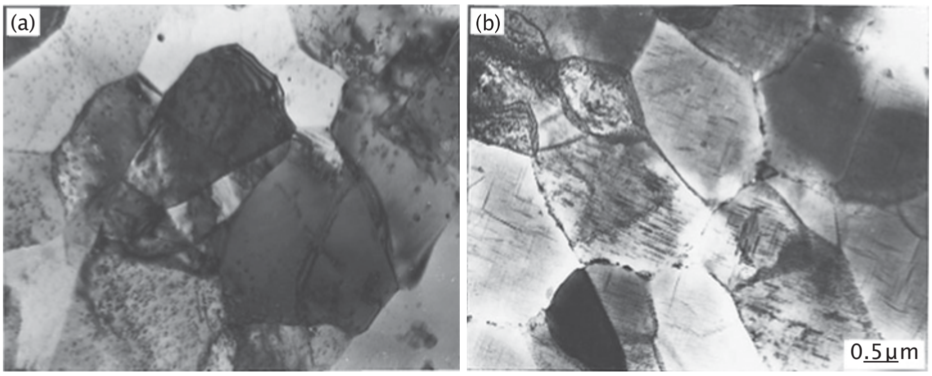

Figure 2.1: Aluminium alloy microstructure in (a) as-quenched state and (b) aged at 473 K for 20 h.

texture of aluminium and its alloys [6]. The composition is planned in a manner to cater for specific structure and texture in aluminium alloys after solidification. Such structure and texture can be achieved through the incorporation of various processing methods such as metal working fabrication methods such as forging, rolling, forming, extrusion, wire drawing, annealing and age hardening [4]. An example of microstructure of aluminium alloy with chemical composition by mass Al-2.23Cu- 1.21Mg-0.93Fe-1.09Ni-0.30Sc-0.30Zr in the as-quenched state and aged at 473 K for 20 h is shown in Figure 2.1.

Apart from the fact that aluminium is one of the most widely available metals known to humans, it has proved to be very useful in areas where strength-to-weight ratio is mostly desired, especially in areas such as kitchen utensils, electronics, automobile, aircraft and military armoury. It has the ability to be successfully alloyed with other metals to give better properties and its numerous fabrication processes can be subjected to make it one of the most sought-after metal. The study is aimed at reviewing the work done on aluminium, its alloy, composites, manufacturing processes and their areas of application. Section 2.2 takes a look at various casting processes that are used for fabricating aluminium and its alloys. Other manufacturing processes for aluminium and its alloys are looked at in Section 2.3. In Section 2.4, the manufacturing processes of aluminium composite materials from various research works are reviewed. At the end, suggestions on what can further be done in this research area and conclusion are presented in Section 2.5.

2.2 Casting processes for aluminium and its alloys

Casting is one of the most important manufacturing processes that are employed in the industries, and castings are produced through remelting of ingots in furnace and then pouring the molten metal in a sand or metal mould [2]. All processes used for casting metal can be applicable for casting aluminium, and the advantages of aluminium castings lie in its ability to be produced to near-net-shape with dimensional accuracy, properties consistency and controlled surface finish [7]. Some of the processes of aluminium casting include investment casting, plaster casting, sand casting, permanent mould and pressure die casting. This section shall be looking at some of these casting processes.

2.2.1 Casting processes

Researchers are continuously interested in developing the best way possible for the casting of aluminium and its alloys using some of the well-established casting processes such as sand casting, die casting and investment casting. Sand casting involves the production of mould by ramming sand into a pattern. The removal of the pattern leaves a cavity in the sand. Sand cores are used to introduce internal cavities in casting. Poured molten metal in the mould is allowed to solidify and the mould is then fragmented to obtain the casting. Sand casting is a cheap and versatile process that makes use of deferent alloy ranges. Among its limitations is its relative poor surface finish and poor dimensional accuracy when compared to other manufacturing processes. However, it is flexible when it comes to the number of castings that can be produced. Figure 2.2 shows the mould for sand casting.

Permanent mould casting is another casting process that involves the pouring of molten metal through gravity into a mould of steel or cast iron. This process is similar to sand casting process. While sand moulds are removed after each casting operation, a permanent mould may be employed in achieving up to 120,000 casting cycles [8]. The process is usually employed in the casting of ferrous and non-ferrous metals. The metal moulds are much expensive to manufacture compared to moulds for sand casting.

Investment casting makes use of refractory moulds that are produced on a thermoplastic pattern or an expendable wax. The refractory slurry is enveloped

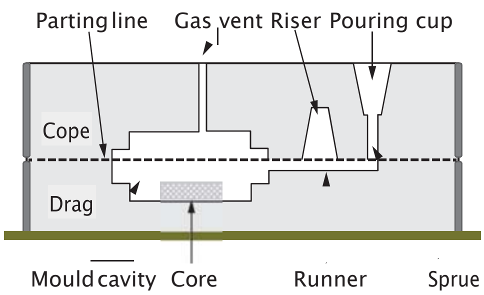

Figure 2.2: Mould for sand casting [8].

around the pattern arrangement. As the refractory dries, the pattern is melted out which then leaves behind a cavity. Molten metal is then introduced into the mould. The advantage of this process lies in the castings produced that may not require further machining. Ability of this process in producing thin walls, fine surface finish and good tolerances makes it useful in the production of precision-engineered parts and components. Figure 2.3 shows the basic steps in investment casting process.

Son et al. [10] investigated effects of neodymium (Nd) inclusion in the microstructure and the mechanical properties of Mg-5Al-3Ca alloy formed using gravity casting and extrusion process. Nd was added to the alloy to give Mg-5Al-3Ca-xNd alloy (x from 0 to 3 mass%). The alloys were formed in a steel crucible under SF_6 and CO_2 atmosphere. The melts at a pouring temperature of 750 °C were casted into a steel mould heated to 200 °C. The as-cast alloys were then held at 380 °C for an hour and extruded into a 12 mm diameter rod at an extrusion speed of 5 mm/s with extrusion container and die temperature of 380 °C. By examination of as-cast extruded alloys under optical and scanning electron microscope with energy-dispersive X-ray spectrometer, it was observed and drawn to conclusion that as the Nd addition increases, the α-Mg matrix morphology transformed from dendritic to equiaxed grains and with average grain size reduction caused by intermetallic compounds containing Nd that was able to suppress grain growth. Also the Nd inclusion to the based alloys lead to the creation of rich Al-Nd intermetallic compounds along grain boundaries and α-Mg matrix grains, with the Al-Nd intermetallic compounds homogenously scattered. Other results obtained revealed that the hardness values of the alloy

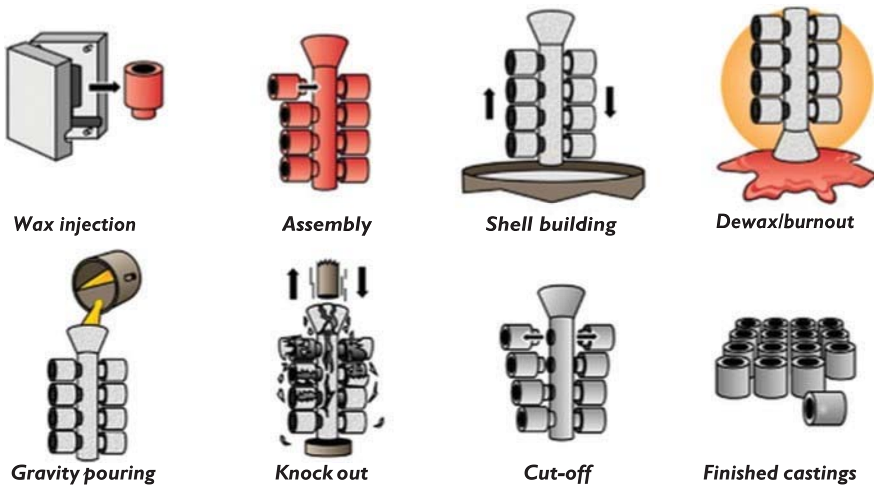

Figure 2.3: Basic steps in investment casting process [9].

were larger when compared to Mg-Al-Ca alloy without Nd. Yield strength and ultimate strength were also improved to 322 and 335 MPa, respectively.

Nakato et al. [11] developed a set of procedures in production of continuous semisolid casting of aluminium alloy billets. In this process, aluminium alloy billets (AC4C) of diameter 75 and 150 mm were cast continuously in a semisolid state, moving the alloy in an agitating container with an electromagnetic stirrer/mechanical screw. It was concluded that the solidification structure of the billets cast apart from the thin chill layer of about 2 mm thick showing a dendrite structure was majorly a mixed of fine eutectic structure and granular particles.

In the study of Raji [12], comparison of grain sizes and mechanical characteristics of Al-Si alloy components obtained through diverse casting process were analysed. Chill casting, sand casting and squeeze casting processes were utilized to produce similar shape and size of Al-8%Si alloy castings. Samples from castings were prepared and subjected to metallographic and mechanical examination. It was noticed in the microstructure that grain size of castings decreases from that of sand casting to chill casting and squeeze casting with the smallest grain size. Concurrently, mechanical characteristics of various castings improve from sand casting to chill to squeeze casting. It was, however, concluded that chill castings and squeeze castings may be utilized in as-cast condition in engineering applications requiring medium and high mechanical properties, respectively. It was then recommended that sand castings may be utilized in as cast condition in engineering applications where medium or high mechanical properties are not essential and could also be utilized in non- mechanical applications.

2.3 Other manufacturing process of aluminium and its alloys

The uniqueness of aluminium and its alloys is seen in their ability to be formed using deferent metal forming or manufacturing processes. Examples of these manufacturing processes are forging, rolling, drawing, extrusion and peening. This section takes a look at this manufacturing processes and related work done on forging process of aluminium in particular.

Rolling: This is a process employed to reduce the shape or cross-sectional area of a metal material through deformation caused by a pair of rotating rollers moving in opposite directions as shown in Figure 2.4.

Extrusion: This is a manufacturing process that involves the shaping of a metal billet by forcing it via a die having an opening. The die is located at the end of an extrusion press container in which the metal billet is placed. As the ram presses the billet as shown in Figure 2.5, the metal begins to flow via the opening in the die thereby producing an extruded product of the cross section desired.

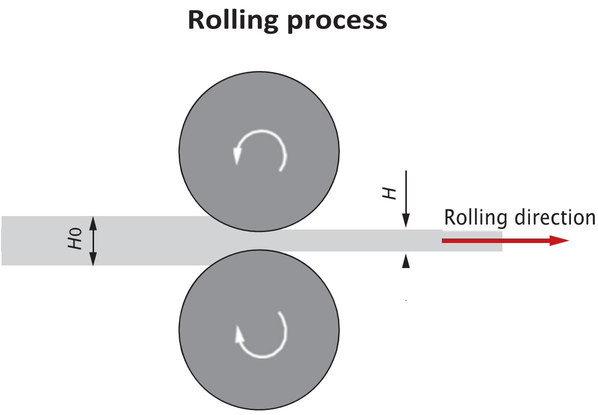

Figure 2.4: Rolling process of a metal piece [13].

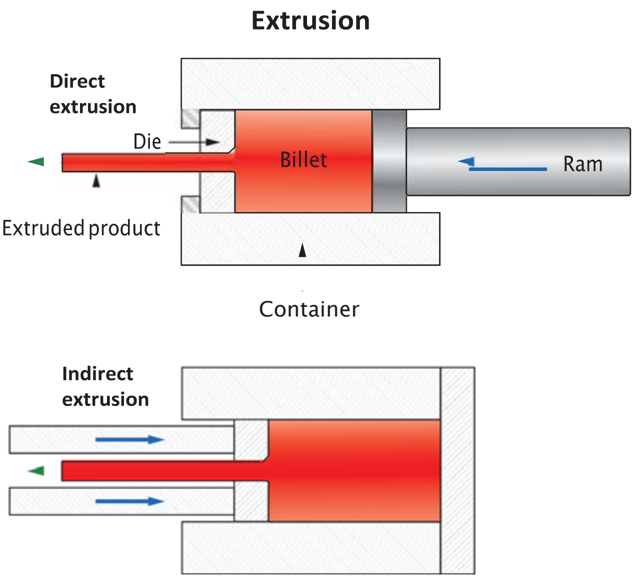

Figure 2.5: Extrusion process of a metal billet [14].

2.3.1 Forging process for aluminium and its alloys

Another manufacturing process used for aluminium and its alloys is forging. Forging involves the heating of metal to a desired temperature where sufficient plasticity is achieved and then followed by other operations such as hammering, pressing and bending to form the metal into a desired shape [2]. Some of the forging processes

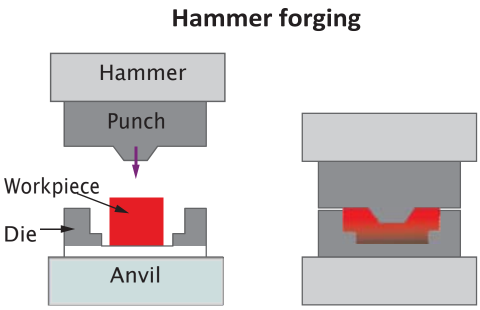

Figure 2.6: Hammer forging of a metal piece [15].

available are smith/hand forging performed using basic tools and basically utilized for little jobs, power forging that makes use of power hammers (as shown in Figure 2.6) noted for average and big jobs that need heavy blows, machine or upset forging that makes use of forging machine and the drop or stamp forging that makes use of drop hammers that make them highly useful in mass production of similar parts.

The temperature range for forging of aluminium and its alloys lies within 350–500°C. Some of the advantages of forging include the refining of the structure of metal, making the metal stronger by setting grains direction, attainment of reasonable degree of accuracy and the ability to weld forgings.

Forging technology has reached an advanced developmental stage where precision forgings are now used in most highly stressed parts like internal combustion engines, aircraft undercarriage gear and other power units. Pleasing grain orientation of metal is achieved in forging process as such; forged items have good grain structures and best mechanical properties combination [16]. Automotive industry is one of the major industries that utilizes forged components followed by machine tool and apparatus industry [17].

Dongre and Salunkhe [18] did a study on the outcome of deformation temperature on 6061 aluminium alloy. Hot compression test was conducted on Al-Mg-Si (6061) alloy on Gleeble thermomechanical simulator at temperatures of 350, 400C and 450 °C and at 0.2 and 2 strain rates for fixed nominal strain of chosen value. Mechanical and microstructural evaluation was conducted for the strain rate and temperature combinations. The true stress–strain graph indicated that at low strain rate and low temperature, flow stress is low and also at the temperature of 450 °C, low stress increases with strain rate as a result of increase of dislocation density and dislocation multiplication rate.

Vaneetveld et al. [19] conducted a study on thixoforging of aluminium alloys (7075) improvement at high solid fraction. The study utilizes a Recrystallization and partial melting (RAP) process with a seven-step heating cycles of 141 s to achieve recrystallization and improve smaller grains in the liquid matrix. Using 0.89 high solid fraction and at an extrusion ratio of 1:16, a homogeneous recrystallization was attained for slug of 35 mm diameter machined to

30 mm. High solidification rate was seen as a setback associated with the high solid fraction. The high solidification rate may be reduced by minimizing thermal exchanges between the tool and part. Some small cracks are seen due to cooling that took place in the tool after thixoforging. Raising the tool temperature to slow down the cooling parts thereby minimizing the cracks was recommended. It was concluded that to achieve an improvement in the quality of thixoforged parts, the tool temperature must be elevated in addition to a suitable punch speed to limit cracking as a result of fast cooling.

Naser et al. [20] did a study on the mechanical behaviour of multiple-forged aluminium alloy. The study was onaluminium alloy 7075 both in the multiple forged and initial states by conducting hardness, cold and hot compression test. The Vickers hardness measurements and optical microscopy images were used to evaluate the homogeneity and structure of the material. A set of constitutive expressions were obtained for the two states and the expressions were able to estimate accurately the flow stress over large range of strain rates and working temperatures. Deformation anisotropy effect is negligible during hot deformation but has a noticeable effect during cold deformation.

In the study of Rathi and Jakhade [21], deferent forging processes were identified and various forging defects were investigated. Repeatedly occurring forging defects, their causes and remedies were discussed. Possible causes of defects such as mismatch, unfilling and scale pits using fishbone diagram and their causes were con- ducted. It was finally concluded that the forging process provides better quality products when compared to other parts producing other processes. It is good to understand and control the process to prevent defects instead of discarding parts with defects at the final inspection stage.

Ball et al. [22] investigated forging residual stress influence on fatigue in aluminium. Design features like holes and machine pockets were introduced in designed and manufactured coupons in areas of deferent levels of bulk residual stress. Multiple methods and modelling utilizing finite element analysis were used in measuring the residual stresses at unstable areas in the coupons. Results obtained from fatigue crack growth (FCG) and fatigue crack initiation (FCI) tests from constant amplitude and spectrum loading were compared with that obtained from computed FCI and FCG. In conclusion, the work indicates that it is possible to achieve reason-able accuracy, and the influence of residual stress on fatigue using simulations.

2.4 Manufacturing of aluminium composite materials

Aluminium alloys and its composites continue to witness tremendous increase in their utilization, most importantly in places of automobile and aeronautic industries owing to their unique properties like low density, low weight, high strength, good wear resistant and coefficient of thermal expansion. Aluminium matrix composites

(AMCs) are range of high class engineering materials that can be employed in numerous applications. AMCs are made up of non-metallic reinforcements (such as silicon carbide [SiC], boron carbide [B_4C], silicon nitride [Si_3N_4], AIN, TiC, TiB_2 and TiO_2) introduced into aluminium matrix to give advantageous properties over the base metal (Al) alloys [23]. Reinforcements in AMCs are normally seen in various forms like continuous and discontinuous fibres, whisker or particulates usually in volume fractions of up to 70% [24].

Different fabrication techniques of composites are in existence. These techniques are normally based on the type of reinforced material (continuously or discontinuously) to be employed in the production of the composite. Vengatesh and Chandramohan [25] highlighted some of the techniques including stir casting technique, liquid metallurgy, gravity and squeeze casting technique.

The squeeze casting is a common technique used in the fabrication of composites of aluminium, where pressure between 70 and 150 MPa unidirectional pressure infiltration is employed. Components produced using this technique are free of void and possesses microstructure of small equiaxed grain size [26]. It is a fast process, producing good surface finishes and with the ability for selective reinforcement usage. Figure 2.7 shows the steps involved in the squeeze casting of discontinuously reinforced composites.

2.4.1 Stir casting method

Stirring is an easy production pathway for particle reinforced aluminium alloys [26]. Mechanical, electromagnetic or gas injection is employed in the stirring operation. Major issues associated with this technique are clustering or

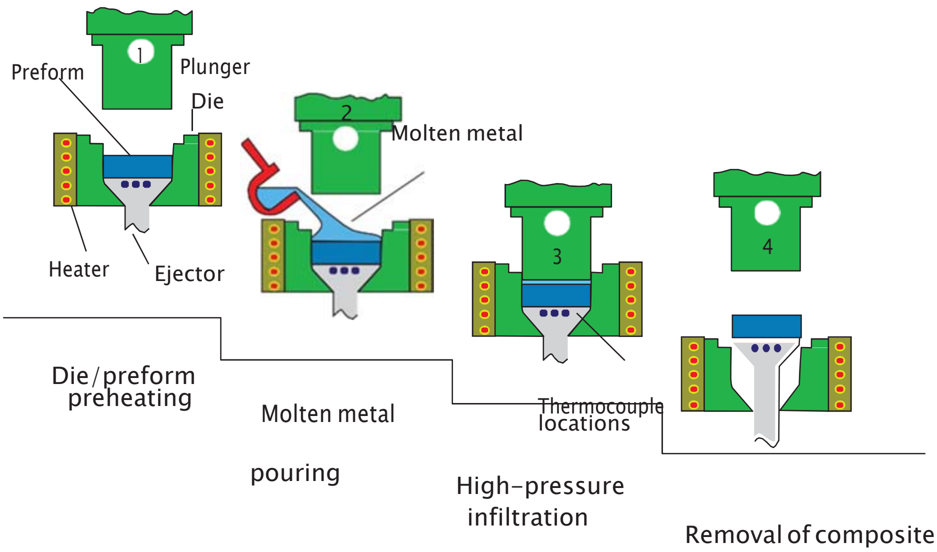

Figure 2.7: Squeeze casting of discontinuously reinforced composites [26].

agglomeration of the particles, displacement of reinforcement by liquid particles and particle redistribution that tends to affect the mechanical properties. These issues are easily taken care of employing several methods such as adding particles to the vortex created by the mixing impeller, preheating of particles before introduction, surface treatment of particles or alloying of the matrix, use of ultrasonic or electromagnetic vibration and addition of particles and metal matrix powder as pellets or briquettes. Figure 2.8 shows the schematic of a stir casting apparatus.

Meena et al. [27] analysed the mechanical properties of Al/SiC (silicon carbide) metal matrix composites (MMCs). MMC bars and circular plates fabricated using melt-stirring technique were prepared manipulating reinforced particles using 5%, 10%, 15% and 20% weight fraction. Rotating speed of the stirring process with a graphite impeller was set to 200 rev/min for 15 min. Microstructure and mechanical properties of the prepared MMCs were studied. Increase in hardness of composites was proportional to increase in reinforced particle weight fraction. The optical micrographs revealed a considerable uniform distribution of reinforced particles using the stir casting technique, leading to decrease in percentage elongation and reduction in area as the reinforced particulate size (220 mesh, 300 mesh, 400 mesh) and weight fraction increase. The impact strength also lowers with increase in the reinforced particulate size but rises with increase in weight fraction of the SiC reinforced particles.

Sambathkumar et al. [28] studied the micro-scale deformation behaviour of aluminium 7075 hybrid MMC using their two-dimensional microstructure with the help of finite element technique. Aluminium 7075 alloy was reinforced with SiC and titanium carbide (TiC) using two-step stir casting technique. Microstructure image obtained from inverted metallurgical microscope was changed to a CAD file format.

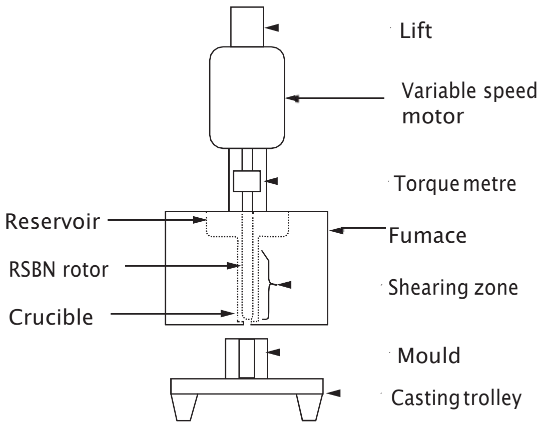

Figure 2.8: Schematics of a stir casting apparatus [47]. RSBN: Reaction bonded silicon nitride.

ABACUS 6.10, a conventional finite element tool, was then used to analyse the model. The stress–strain behaviour of the composites was analysed by varying the percentage volume of reinforced particles in ranges of 5%, 10% and 15%. The result revealed that 15% by volume percentage (SiC and TiC) aluminium composites has a maximum strength of 1,713 MPa. It was concluded that as the volume percentage rises, the strength of the hybrid MMC also rises and that 15 vol% microstructure was stronger during uniaxial tensile loading as compared to the other two.

Toptan et al. [29] carried out a study to investigate the influence of titanium inclusion on the properties of Al–B_4C interface. Average particle size of 52 µm B_4C particles utilized as reinforcement in pure aluminium (AA 1070) was used as matrix material with the addition of K_2TiF_6 flux to form a reaction layer containing TiC and TiB_2 at the interface as a way of increasing interfacial and wettability bonding. Aluminium was melted in boron nitride-coated graphite crucible to produce particulate reinforced AMCs. The microstructure of AMC specimens was studied under optical microscope and scanning electron microscope. It was discovered that due to poor wetting of B_4C particles by liquid aluminium, effective bonding was not achieved at lower temperatures as 850 °C. The addition of K_2TiF_6 flux creates a thin reaction layer of TiC and TiB_2 that solved the wetting issue. Superior mechanical and tribological properties were exhibited by Al6061-SiC composites.

Sekar et al. [30] designed a stir casting machine. The component parts such as the stirrer shaft, die, nanoparticle preheated and heating vessel were calculated for and drawn using a three-dimensional solid model. The design aids the pouring of molten metal into the die at a constant temperature before crystal growth starts because the die and the furnace are connected via a pathway taper pipe channel with heater. The machine had been used in the production of A356/Al_2O_3 nanoparticle composite materials. Sahoo et al. [31] also worked on stir casting furnace design and fabrication. The two main parts of the stir casting furnace (furnace elements and control panel) help execute the casting operation. The machine was used in the melting of aluminium scrap and the molten metal was then casted.

Sujan et al. [32] worked on the physiomechanical properties of aluminium MMCs reinforced with aluminium oxide (Al_2O_3) and SiC. Performance of stir cast Al_2O_3SiC reinforced aluminium composites was studied. Al356 alloy powders were mixed with Al_2O_3 particles (particle size 400 µm) in 5%, 10% and 15% weight fractions. Al356 alloy powders were also combined with SiC using the same weight fraction to produce Al-Al_2O_3. Samples were melted in the furnace using a temperature of 700 ° for 2 h, then stirred and allowed to solidify in a plate inside the furnace. The samples were machined and then tested. The test result revealed that there is great enhancement in hardness and tensile strength compared to Al356 alloy. The composite materials also indicate higher strength-to-weight ratios when compared with 100% aluminium. Lastly, the wear rate significantly reduces as the reinforcement particles were added with Al-Al_2O_3 exhibiting higher wear rate compared to Al-SiC composites.

Sahoo et al. [33] worked on the fabrication of aluminium alloy (Al-7Si)/titanium diboride reinforced composites using the melt stirring technique. Studies on hardness and microstructure and of direct cast composite Al-7Si-5TiB_2 and Al-7Si-5TiB_2 composite cast through cooling slope method were performed. It was discovered that the grains of TiB_2 are spheroid in shape and finer in composite obtained from the cooling slope method. The fine and spheroid nature of the grains are responsible for the increase in hardness of the composite. The study finally concluded that fabrication of Al-7Si-5TiB_2 using the stir casting technique delivered good end product, TiB_2 addition to A356 alloy increases the wear characteristic of composite and hardness.

2.4.2 Powder metallurgy

Powder metallurgy is regarded as the most common solid-state route but tends to be more expensive compared to liquid-based route [26]. Advantage of the solid-state route is the ability to achieve good mechanical properties as a result of low processing temperature that leads to low reinforcement and matrix interaction. Solidification defects such as porosity, shrinkage and segregation do away with and more consistent reinforcement distribution is achievable. Figure 2.9 shows the powder metallurgy processing route.

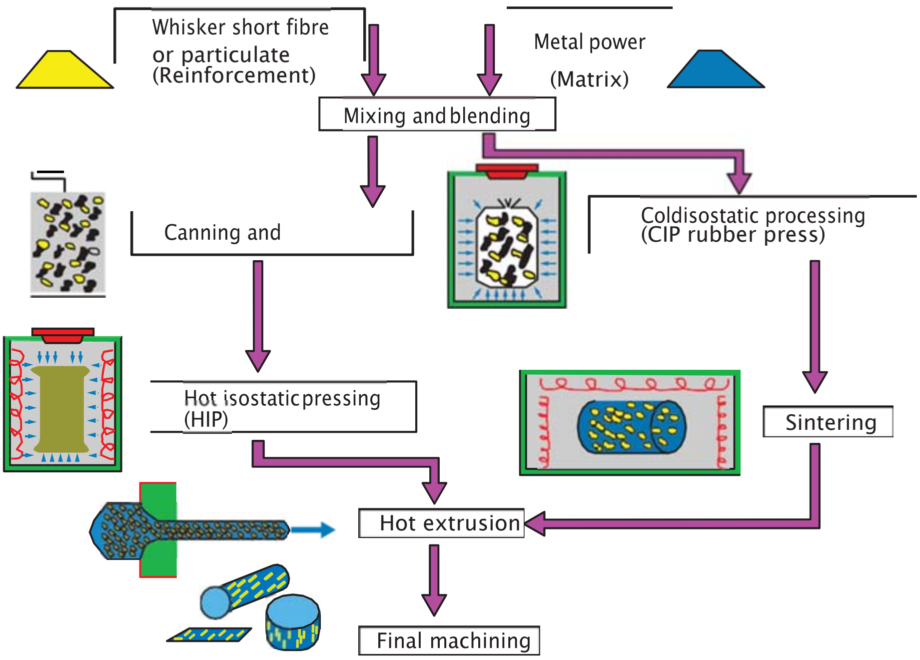

Figure 2.9: Steps for powder metallurgy processing route [26].

Chen et al. [34] carried out a study on aluminium powder size and microstructure effect on the properties of boron nitride reinforced AMCs fabricated through semi-solid powder metallurgy technique. Hexagonal boron nitride was reinforced with an aluminium alloy to form aluminium composites using semisolid powder metallurgy route. Analysis of the powder morphology and structural attribute of composites was carried out using x-ray diffraction, scanning and transmission electron microscope. It was observed that composites processed using aluminium powder with deferent granularity shows deferent grain attributes. It was also noted that there is an increase in the fracture strain and compressive strength of composites with reduction in aluminium powder size and the Brinell hardness.

Kumar et al. [35] presented experimental results on Al6061-SiC and Al7075-Al_2O_3 MMCs. Composites were produced using liquid metallurgy, where 2–6 wt% of particulates were added to the base matrix. Al6061-SiC and Al7075-Al_2O_3 composites and castings of base alloys obtained were finished by machining and subjected to tests. It was observed that the increased reinforcement's percentage increases the density and density of the composites. Micrographs of composites showed consistent distribution of particles in the samples. The tensile strength of the composites was enhanced through the dispersion of SiC and Al_2O_3 in Al6061 and Al7075 alloys, respectively.

Venkatesh and Harish [36] did a study on the mechanical properties of Al/SiC_p MMC particles fabricated through powder metallurgy route. SiC particles of mesh sizes 300 and 400 and of weight fraction 10 and 15 wt% were mixed with the aluminium matrix and four deferent samples were obtained. Microstructural and mechanical tests were performed on the samples. The results revealed that the hardness and density of MMCs were increased with increase in sintering temperature. It was also noted that as SiC_p increases, the density of composites increases and hardness of composites increases with rise in weight percentage of SiC_p in the composites and mesh size.

2.5 Functionally graded materials of aluminium composites and research direction of manufacturing of these composite materials

Functionally graded materials (FGMs) are advanced composite materials with properties varying across the volume of the materials [37]. Aluminium matrix FGMs have been produced using deferent fabrication technologies and some of which are presented in this section. Radhika and Raghu [38] investigated the microstructural properties of Al/SiC, Al/B_4C, Al/Al_2O_3 and Al/TiB2 functionally graded composites with a consistent 12% (mass fraction) reinforcement fabricated using centrifugal casting. The microstructural properties at exterior surfaces of all composites were found to contain segregation of reinforcement particles. Graded properties in terms of tensile strength and hardness of the composites were also investigated. The results showed higher hardness along the outer peripheral of all the composites with the exception in Al/B_4C compo- site while all the composites display high tensile strength. The wear rate was also found to be reduced in all the composites. The centrifugal casting has been found to be an important fabrication method for fabricating FGMs with a well- controlled compositional gradient taking advantage of the centrifugal force and the density differences between the materials [39]. The microstructures of the fabricated FGMs are mentioned in Figure 2.10, showing the graded microstructure of the reinforcement particles in deferent densities at deferent locations.

A similar study was carried out by Duque et al. [40], where the fabrication of aluminium alloy FGM reinforced with AlB_2 particles was done through the centrifugal casting method. The study showed that the produced FGMs have improved corrosion resistance when compared to the parent material. The study also revealed that the centrifugal casting process was effective in redistributing reinforced particles and in graded form. The process has been proved to improve the corrosion resistance of the FGM produced [41]. Powder metallurgy is another important fabrication technique employed in the fabrication of FGMs [39].

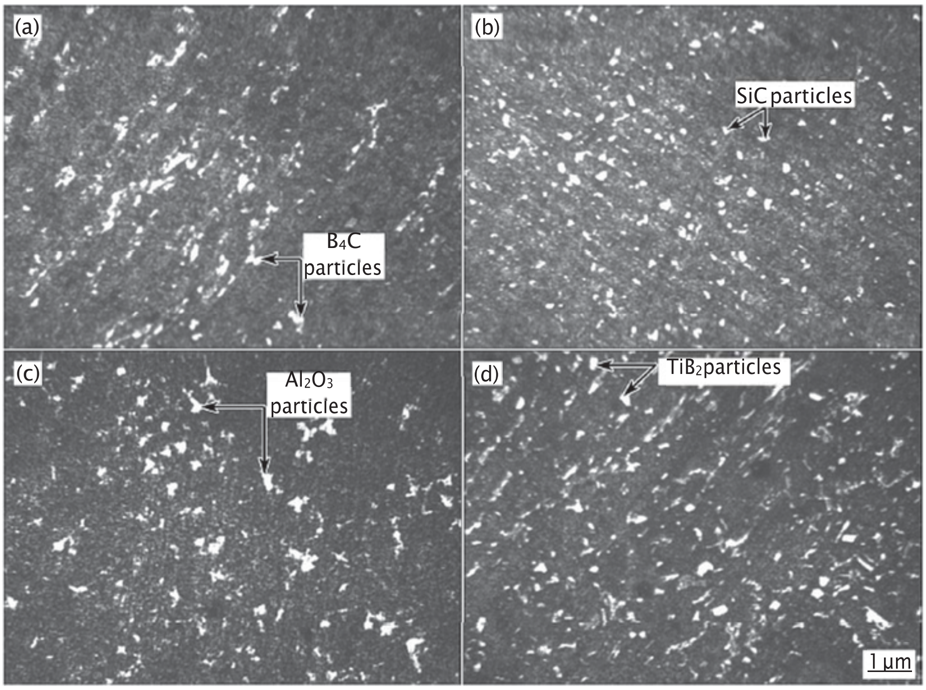

Figure 2.10: Microstructures of FGMs: (a) Al/B_4C; (b) Al/SiC; (c) Al/Al_2O_3; and (d) Al/TiB_2 [38].

Udupa et al. [42] using powder metallurgy with cold compaction method investigated the fabrication of functionally graded carbon nanotube (CNT) strengthened aluminium matrix laminates. The CNT particles were introduced to the aluminium matrix in separate weight fractions from 0.1 to 0.5 wt%. Studies on the mechanical proper- ties of the functionally graded composites produced were carried out in order to assess how effective the fabrication method was. The results showed that the powder metallurgy technique is an effective method that can be used to alter the material properties as needed. The graded microstructure of the composite is shown in Figure 2.11, where the CNT reinforcement changes from pure Al to 0.5 wt% CNT from one end to the other end of the sample. In each layer where variation of CNT reinforcement changes from pure Al to 0.5 wt% CNT from one end to other end of the sample showed deferent microstructures with variation in the densities of the CNT particles. This was further confirmed by the hardness variation obtained from one end to the other with a hardness increment of up to 129% achieved with that of 0.5 wt% of CNT in the formed laminates with every layer showing strong metallurgical bonding after the sintering process with no significant micro cracks or pores.

Çalıskana et al [43] carried out a similar study using the powder metallurgy technique. In this study, Al2124/Al_2O_3 powders of functionally graded composites were produced in various compositions. The study revealed that the transition zone can be designed to be gradual as shown in Figure 2.12 by gradually varying the composition and structure over the entire volume of the functionally graded AMC. The FGMs produced were also found to have improved properties that vary across the volume of the composites.

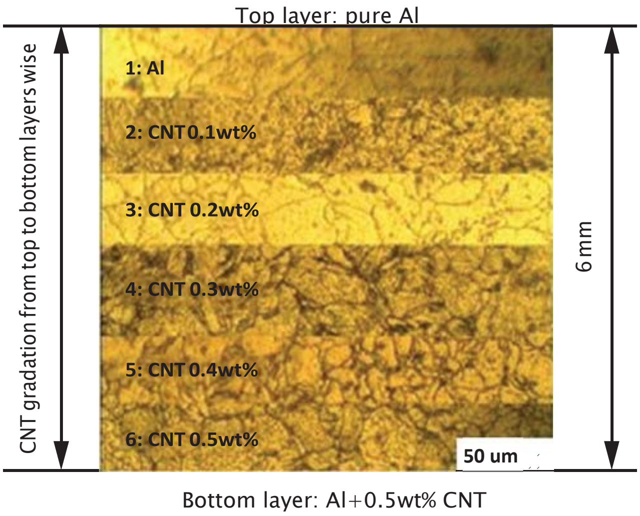

Figure 2.11: Functionally graded composite materials of Al with CNT reinforcement macrostructure with deferent layers [42].

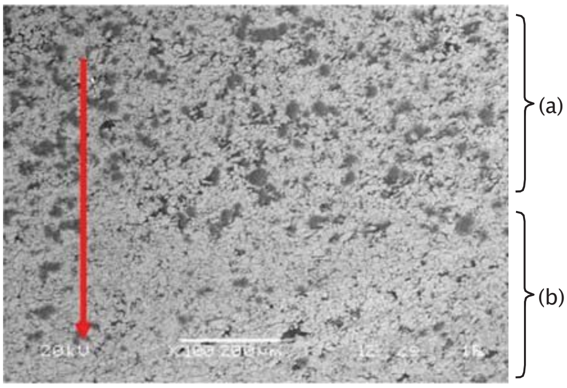

Figure 2.12: Transition zone from (a) 10 wt% Al_2O_3 reinforced material to (b) Al2124 alloy [43].

Kwon et al. [44] carried out a similar study by producing functionally graded CNT reinforced AMCs using the powder metallurgy method. The gradient layers were observed to contain various amounts of CNT as shown by diverse microstructures and hardness. The Al-CNT functionally graded composite revealed fine particle size distributions with increment in the amount of CNT addition. Hardness was found to increase with an increase in the content of CNT added. Singh and Singh [45] developed a functionally graded Al/Al_2O_3 composite using an alternative reinforced fused deposition modelling (FDM) pattern in investment casting process. The study revealed that the FGM offered better mechanical properties and improved tribological properties.

Investigation into the fabrication technique of composite materials is a vast area still experiencing continuous investigation, where possibilities on improving the properties of composites and test for most suitable means of mass production are continuously investigated. Researchers have developed fabrication techniques. These techniques cannot be taken as the only technique for composites preparation as composite fabrication is a wide area where great possibilities for creation of a better, cheaper method or new techniques that may serve as an improvement to existing ones are possible. Additive manufacturing (AM) technique such as laser metal deposition (LMD) technique is a recent area of manufacturing technique now explored in the fabrication of FGMs such as titanium and aluminium alloys [46]. The technique uses metal powder and computer-aided design model data for layer-by-layer build-up of components. Material waste reduction, reduction in downtime and production of components with unique properties are some of the advantages of this technique. Components manufactured using this technique are gaining applications in sectors such as aerospace, medicine and surgery, automobile, energy, electronics and other manufacturing industries requiring high-performance components.

The development of more powerful finite element simulation tool with great accuracy to enhance analyses of composites model is encouraged, where stress–strain behaviour by varying percentage volume of reinforced particles is achievable to study the characteristics of composites. Also development or improvement in established technique and equipment are needed in increasing interfacial and wettability bonding in composites. Finally, adequate tests including Machinability are needed to be carried out on fabricated composite materials to fully establish their properties, area of application and possible failures.

2.6 Summary

Aluminium is one of the most plentiful raw materials found in the Earth's crust and never found in its pure state, as such careful practices must be done to obtain the metal in pure form. Its unique characteristics allow it to be alloyed and reinforced with other materials to produce alloys and composites with better qualities. Casting and forging are essential methods in the manufacturing of aluminium and its alloys. Production of products of near net shape with little need for subsequent machining is some of the characteristics of these manufacturing processes. The need for new products (mostly in automobile and aeronautic industry) with superior attributes such as low density, low weight, high strength and wear resistance made the production of composite materials with numerous applications an area of research that is vast. Fabrication technique of these composites depends on the type of reinforced material to be used. Notable among the techniques are stir casting, powder and liquid metallurgy and squeeze casting. AM such as LMD is a recent technique used in the fabrication of FGMs that are now finding applications in aerospace, automobile, medical, energy, electronics and other high-performance applications. Great successes are continuously recorded in the area of composites development but more still need to be done especially in carrying out an accurate and precise test in determining the properties of fabricated composites. Development of powerful tools for finite element simulations where percentage reinforcements by weight can be varied, the result is generated and studied. The fabrication methods of composites and functionally graded aluminium composite materials are presented in this chapter and the research direction has also been highlighted.

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