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Influence of Various Parameters on The Properties of Aluminium Metal Matrix Composites (AMMC's): An Overview

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Abstract:
Composites have gained wider acceptance attributed their superior mechanical properties such aslight weight, high strength, stiffness, fatigue behaviour, wear resistance, etc. at various service temperatures. This leads to the use of composite materials quite significantly in aerospace and automobile industries. This paper reviews in detail the outcome of various research work carried out earlier and current understanding in production of aluminium metal matrix composite (AMMC). It is observed that, stir casting is generally used as a method of producing MMC because of its simplicity, economical and yields fairly uniform properties compared to other methods. Parameters such as operating temperature, stirring time, and stirring speed are reviewed critically. Selection of reinforcementsand its effects, effect of distribution, and volume fraction are reviewed and discussed. The effect of preheating and coating of particles are discussed and finally concluded with the scope for future areas of work.

Keywords —**Aluminium metal matrix composite, Particle size, Reinforcement**

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I. INTRODUCTION

Composite materials have gained significance interest in recent years due to their superior physical and mechanical properties compared to conventional metals, which are stronger, lighter and less expensive when compared to traditional materials.Now a days these materials find regular use in buildingaircraft structures, automobiles, bridges, structures.etc.[1]

Composite materialsgain enhancement in properties based on the interaction between the matrix and the reinforcement.The primary function of the reinforcement in aluminium metal matrix composite (AMMC) is to carry most of the applied load, where the matrix binds the reinforcements together, and transmits and distributesthe external loads to the individual reinforcement [2]. Good wetting is an essential condition for the generation of a satisfactory bond between particulate reinforcements and liquid aluminium metal matrix during casting composites and it allows transfer and distribution of load from the matrix to the reinforcements without failure. Strong bonds at the interface are required for good wetting. These bonds may be formed by mutual dissolution or reaction of the particulates and matrix metal. The reaction phenomena are very detrimental to the composite as they may decrease of the mechanical properties of the composite[3].Weaker interfacial attraction between the matrix and reinforcement causes the damage to the matrix material. Different processing, treating the reinforcement with other

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materials for interfacial bonding can improve the matrix and the reinforcement interactions. One method is to apply external pressure to compel close contact between reinforcement and matrix to promote wetting. Among other methods, squeeze casting is considered be a good choice. The other commonly used processing methods are, solid-state processes, powder metallurgy in situ processes and spray-forming of particulate AMMCs, [4, 5].Variety of metals can be used with different reinforcements, diffusion of particles and volume fraction can be very easily achieved using this technique. This process is expensive, time consuming, needs high energy to operate and has to be operated at high temperatures and pressures and is limited for only simple shapes.

The method of fabrication process and reinforcement size and type are the major factors influencing the physical and mechanical properties of the composites [6]. It is observed that,continuous fiber reinforced AMMCs are expensive and their applications are therefore limited because of weaker interfacial attractions and propagation of crack along the length of the fibre [7]. On the other hand discontinuously reinforced AMMCs results in improved mechanical and physical properties that cannot be achieved using conventional engineering alloys [8].

Among the different types of metal matrix composite (MMC), hybrid aluminium matrix composites using ceramic preform or alumina (Al_2O_3) whiskers and high-pressure casting have also generated significant interest as they provide the best combination of tribological properties, strength, and toughness, and can be manufactured using conventional processing techniques. Therefore, cast hybrid MMCs, which contains the preform material and SiC particles as the wear-resistant material, have been gaining equal usefulness in aircraft, automobiles, and other transport vehicles, [9-11]. The aim of this study is to critically review the different influencing parameters on the properties of aluminium metal matrix composite (AMMC).

2. Literature

2.1 Processing parameters

It is paramount to consider appropriate production technique for MMC's. Powder metallurgy method utilizes high energy for compaction and relatively expensive, it provides uniform distribution of reinforcements and reduces the porosity in the component. Its operating parameters makes it uneconomical and often known for fracturing the reinforcement and intermetallic inclusions during the process[12]. Spray forming on the other hand often attracts less attention because of its complex working nature. It is expensive and not all materials and shapes can be produced by this method [13]. Squeeze casting technique eliminates blow holes and produces structurally sound casting. It requires high mechanical pressure to extrude and relatively expensive process. The reinforcement is severely damaged during this process and surface condition relies on applied pressure, operating temperature and squeezing rate [14].

Stir casting is cheaper and effective in terms of maintaining particles in free state and disperse the particles into the liquid metal. [15, 16]. The stirrer rotation creates the vortex this helps in distributing the particles evenly in the melt [17, 18]. Table 1 shows the comparison of stir casting with other methods. Stirring parameters such as, impeller type, impeller blade angle, holding temperature and stirring speed, are optimized for homogeneous distribution of particles [19]. It suggested three to four turbine blades with 60° is considered good for homogeneous distributionof the particles.[20]. It is observed that melt temperature should be higher than the melting temperature of the matrix material to maintain low viscosity of melt. This increases the probability of homogeneous distribution of particle and particle retention. [21]. However, researchers found that the wettability of the particle and the particle distribution is significantly dependent on melting temperature and holding temperature [22].

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It is observed that it is essential to break the gas layer to a superior wettability between reinforcement and liquid metal.[23]. The mechanical stirring can overcome the surface tension to improve the wettability. However, stirring parameters need to be controlled and excessive stirring may not produce any good result.

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Table1: Stir casting Comparison with other methods [24]

Process	Range of shape	Range of size	Metal Yield	Damage to reinforcement	Cost
Stir casting	Wide	Larger size	Very high	No damage	Least expensive
Squeeze casting	Limited	Restricted size	Low	Severe damage	Moderately expensive
Powder Metallurgy	Wide	Restricted size	High	Reinforcement fracture	Expensive
Spray Casting	Limited	Large size	Medium	---	Expensive
Lanxide Processing	Limited	Restricted size	----	---	Expensive

It is evident from the reference that the particle clustering is observed for lower stirring speed and lower stirring time for Al-SiC composite. The trend is improved as the stirring speed increased to 400 rpm with 10 min stirring time. This resulted in better distribution of particles and uniform hardness values. It is also observed that at higher stirring speed the particles are un uniformly distributed. And it is finally concluded that at 600

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rpm and 10 mins stirring time is optimum conditions for better hardness and homogeneous particle distribution for a composite [25]. A similar variation has been evidenced and documented for a composite produced by stir casting method and similar range of operating conditions is concluded [26]. Guan Li-na et al. [27] reported that the uniform distribution of reinforcement and increase in tensile properties with the stirring temperature at 640 °C maintainedup to 30 mins. Sozhamannan et al. [28] found that, higher holding time increased the formation of particle clustering. Many researcher have concluded that stir casting is one of the best method to prepare the AMMC's

2.2 Particle size and volume fraction

Particle size and volume or weight percentage of reinforcement is the important factors in accessing the property of the composite. Particle size and volume fraction plays a vital role in improving physical and mechanical properties of the AMMCs which can be determined by measuring the density, hardness and tensile strength values. Varol and Canakci [29] observed that, with an increase in the weight fraction of reinforcement, density decreases with increase in hardness. W. Zhou and Z. M. Xu [30] makes the similar conclusions and this is evidenced by the results shown by Pramanik et al. [31] that hardness value depends on the volume percentage of reinforcement. Table.2 shows an increase in porosity with increasing in micro and nano Al2O3 and decrease in flow of metal due to poor nucleation at the particulate surfaces. Investigators S.A. Sajjadi et al. [32] reported that good wettability of particles in compo-casting and low porosity compared to stir casting process. Lower the porosity, better the wettability between the matrix and the reinforcement particles as well as the lower volume shrinkage of the composite [33].

Table 2 The porosity percent of micro and nano-composite fabricated by compo and stir casting process data from [32].

Micro/nano-composite	Porosity (%) (Stir casting)	Porosity (%) (Compo casting)
A356	1.11	1.11
A356–1 wt.% micro-Al_2O_3	1.18	1.15
A356–3 wt.% micro-Al_2O_3	2.05	2.05
A356–5 wt.% micro-Al_2O_3	2.9	2.85
A356–7.5 wt.% micro- Al_2O_3	5.6	5
A356–1 wt.% nano-Al_2O_3	1.18	1.12
A356–2 wt.% nano-Al_2O_3	1.62	1.5
A356–3 wt.% nano-Al_2O_3	2.41	2.25
A356–4 wt.% nano-Al_2O_3	–	3.5

Further the ductility variation with different manufacturing techniques are being observed in the Table 3, that the variation of ductility as the weight % increase in Al2O3 for both stir casing and compo casting which is the result of poor wettability of the particles in the material and increase in the hardness of the material. Hansang Kwon et al. [34] adapted advanced powder processing method by combining hot extrusion and spark plasma technique, and found that by adding 5% by volume of carbon nanotube to the AMMC, increases the strength by three times. In general, variation in particlesize results in variation in material strength. As the grain size increases, hardness increases and porosity decreases.

Further studies on the effect of particle size are contradictory. Chawla et al. [35] observed that fatigue strength increased with decreasing particle size. On the contrary, Bonnen et al. [36] show no improvement of fatigue strength even in the composites reinforced with small SiC particles. On

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the other hand the authors have reported that the critical particle size was 20 microns below which fatigue strength was the same as the unreinforced alloy, or slightly increased with decreasing particle size [37]. Therefore, it is necessary to further understand the effects of particle size on fatigue behaviour and particularly important to realize its role in crack initiation and small crack growth, because fatigue life is usually dominated by those processes [38]

Micro/nano-composite	Ductility (%) (Stir casting)	Ductility (%) (Compo casting)
A356	1.55	1.55
A356–1 wt.% micro-Al_2O_3	1.45	1.48
A356–3 wt.% micro-Al_2O_3	0.94	1
A356–5 wt.% micro-Al_2O_3	0.83	0.87
A356–7.5 wt.% micro- Al_2O_3	0.65	0.7
A356–1 wt.% nano-Al_2O_3	1.31	1.37
A356–2 wt.% nano-Al_2O_3	1.21	1.29
A356–3 wt.% nano-Al_2O_3	1.12	1.19
A356–4 wt.% nano-Al_2O_3	–	0.74

Reports of Holcomb [39] and Hall et al.[40] shows that for aluminium metal matrix composites, stress-controlled fatigue life is increases with decreasing SiC particle size. The materials contains coarse particles have a tendency for lower fatigue strength mainly attributed to weaker interfacial bonding between particle and sometimes particle cracking. A clear relation between increased particle cracking with increase particle size was observed by J. Hall, etall [40] and S. Holcomb: [39] and the result is observed by D.J. Lloyd [41].Couper et al [42], further, that the size distribution of the reinforcement particle is significant parameter. By decreasing the range of particle by 15%, the fatigue life was observed to be increased due to fracture of larger particles in the distribution is nullified. Increasing the reinforcement led to higher elastic modulus, improved yield strength, and increased ultimate strength, with a corresponding decrease in ductility.

Several authors [43–46] observed the similar trend. Smaller particle sizes for a given volume fraction of reinforcement resulted in higher strength levels. With largest particle size, strength values were found to be substantially below that of the base alloy [47]. It is also observed by Judy N hall [48] that the ductility of the material is reduced with the increase in the particle size.

For a constant reinforcement volume fraction, finer reinforcement particles has less interparticle spacing as compared to the composite with coarse particles. This is to be observed as the volume of the aluminium matrix around a reinforcement particle in the coarse particle is larger than that in the fine particle composite. Therefore, the reinforcements in the small particle composite probably share more portion of loading, giving rise to higher monotonic tensile strength and cyclic stress stresses [49].

2.3 Particle distribution

In general, the problem of nonhomogeneous particle distribution occur due to density difference between reinforcement particles and the matrix material [50] The reinforcement distribution is influenced by several parameters such as distribution in the liquid while mixing, distribution after mixing before solidification, and redistribution as a result of solidification. The mechanical stirrer used during stirring, the melt temperature, type, amount and nature of the particles are some of the main factors considered while investigating the process. The scattering of the particles in a matrix is also affected by pouring rate, pouring temperature and gating systems [51]. The method of the introduction of particles into the matrix melt is one of the important step of the casting process. It helps in scattering the reinforcement materials in the melt. There are a number of techniques are introduced by different

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researchers [52, 53] one of the methods is to inject the particles carried by an inert gas [54] which helps in pushing the particles for greater distance from each other by avoiding the cluster formation. For superior mechanical properties, particle distribution should be uniform for better load baring capacity and improved mechanical properties [55].

Good composite strength requires uniform reinforcement distribution.[56,57] of the many factors the most important ones are wettability and density difference which controls uniform distribution of reinforcement in metal melt [58,59]. Density of reinforcement and matrix material, should alike as much as possible for uniform distribution. Baghchesara et al [60] observed change in material density with reinforcement amount and casting temperature during metal matrix nanocomposite fabrication the most improved compressive strength was obtainedwith the specimen including 2.5% of MgO sintered at 625°C. A good distribution of the dispersed MgO particulates in the matrix alloy was achieved. It is suggested for an optimum casting temperature and reinforcement concentration for better particle distribution [61].

2.4 Pre treatment

2.4.1 Temperature

Structural components for the aerospace and automotive industries are often subjected to severe thermal and mechanical loads and simultaneously aerodynamic heating also affecting on the material. Laser irradiation, localized intense fire and other mechanical loads are generally expected during the course of operation [62–65]. Thermal load leads to intense thermal stress concentration on the material due to the mismatchof thermal and mechanical properties between the metal– matrix and reinforced particle. This concentration of thermal stress around the defects and joints often results in catastrophic failure of components. The applied thermal and mechanical loads are usually cycled, such as cycled thermal load and constant mechanical load, cycled mechanical load and constant thermal load or cycled thermal load and cycled mechanical load. Therefore, it is necessary to study the properties of MMC subjected to the combined loads with thermal and mechanical cycled loads. Generally, the quenching method produce thermal fatigue in the structure [66].

Fully reversed axial fatigue tests for silicon carbide (SiC) aluminium alloy components for different particle size with constant wt% have been performed at 150oC and 250oC.Regardless of particle size, fatigue strength decreased with increasing temperature with a remarkable reduction at 250oC is observed [67]. It is also observed that the fatigue strength depends on particle size at ambient temperature. While the dependency reduces at 150oC and almost become negligible at 250oC. Crack initiation depended on temperature and particle size and small crack growth rates were an order faster at 250oC than at ambient temperature and 150oC in all materials are also being studied [67]. It was indicated that the softening and associated loss in strength of the matrix at elevated temperatures were the primary causes for the temperature and particle size. Han N L[68] conducted experiment on low cycle fatigue life and cyclic stress response characteristics of SiC particulates reinforced pure aluminium and unreinforced matrix aluminium at 298oK and 441oK, and observed that cyclic stress response of the unreinforced matrix aluminium, in the as-extruded condition, revealed initial cyclic hardening, cyclic stability and second hardening at ambient temperature. With a contrast, the unreinforced aluminium at elevated temperature showed progressively cyclic softening behaviour without initial hardening. The induction of fatigue life of the unreinforced aluminium was faster than that of the composite, so the fatigue resistance of the composite was stronger than that of the unreinforced aluminium under lower cyclic strain ranges at elevated temperature.

The test conducted by Nieh, T. G et al[69] for 25 vol% SiC particulate-reinforced 6090 Al composite at 300oC. Results show that at 300oC,

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test samples exhibit large ductility during high-cycle fatigue deformation strain increases with increasing cycles-to-failure and crack growth occurs through plastic deformation of the matrix without particle fracture. The results were also evidenced by Wang, Lei [70]. The major change in fatigue response in temperature from 20oC to 300oC appears to be the mechanism of fatigue crack growth. Fatigue crack initiation mechanisms remain largely unchanged.

2.4.2 Coating

Coating finds its wider application in all fields and MMC are no exception especially in aerospace application. In spite of excellent bulk mechanical properties, aluminium alloys shows poor surface properties, particularly in relation to applications that require wear and corrosion. Tests for 7075-T6 aluminium alloy shows that for rotating bending in both air and in a 3% NaCl solution with a WC–10Co–4Cr cermet [71].

The results indicate that the presence of the coating gives rise to a significant increase in the fatigue strength of the substrate and therefore, the fatigue behaviour point of view this coating could be a feasible. This disadvantage has led to the extensive use of hexavalent-chromium-based conversion coatings (HCCC), such as electrolytic hard chromium (EHC) plating and chromic acid anodizing (CAA), in order to improve their surface properties [72–76]. It is well known that these treatments utilize chemicalsthat contain hexavalent chromium, which is a carcinogenic substance subjected to a strong health and environmental international regulation [77–79]. EHC plating not only gives rise to a significant decrease in the fatigue properties of both ferrous and non-ferrous substrates, which represents a critical aspect for the aeronautic and aircraft industries. Also, it has an unreliable performance, and delaminates in service and promotes hydrogen embrittlement in ferrous alloys[80,81].

3. Conclusion

As the requirements of manufacturing industry is increasing day by day the development of new and cost effective materials with increased mechanical and thermal properties are more essential. Composite materials play a vital role in the ever demanding applications. Development of innovative methods leads to more advanced materials which perform best at all conditions. Metal Matrix Composites is one of the materials which finds its applications in all industries. This review article gives a condensed insight in to the various processing techniques and parameters influencing the process such as fabrication method, particle size and percentage of reinforcement, stirring speed, stirring time, temperature etc. discussed. It is found from the various sources that processing parameters are crucial to produce sound and defect free casting components.

Enhanced mechanical properties achieved at every processing stage together with improved production rate. Stir casting being the simplest and economical in comparison with compo-casting extrusion, powder metallurgy and spray casting . The influence of various parameters at different operating conditions, size, shape, and morphology of reinforcement particles is discussed in detail. Furthermore, process variables such as stirring speed, time, temperature the weight percentage of reinforcement and its effect on the material is discussed in detail. The critical processing steps that must be optimized, as reported by many authors, is the solidification time, stirrer rpm, holding temperature for better particle distribution. It is observed that a lot of research needs to be carried out in order to fully understand factors such as solidification time, dissolved gas in the melt, gas entrapments due to incomplete evacuation, pre-porosity due to incomplete infiltration, yielding the different AMMC structures.

Furthermore, behaviour of metal matrix at different operating temperature needs to be understood since not much work is done in this

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particular area. Similarly more insight has to be sought in application of coating as suggested by many researchers limited work is carried out. Recent processing techniques in the development of aluminium metal matrix composites involve high cost and maintenance. However, no special attention is needed in conventional method of fabrication. Energy efficient, cost effective and simple method of producing composites is the need of the hour. Perhaps stir casting is still the simplest, versatile and most economical processing technique compared to all the other technique.

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