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Synthesis of Metal Matrix Composites via Powder Metallurgy Route: a Review

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Powder Metallurgy (P/M) is playing a vital role to synthesize variety of materials in the field of aerospace, automobile, ordnance, petroleum and petrochemical industries. P/M is an outstanding process to produce components with good mechanical and tribological properties such as strength, hardness, impact resistance and wear resistance. Recently metal matrix composites (MMC) replace conventional alloys because of their extraordinary characteristics. Currently Aluminium, Copper, Magnesium, Titanium and Iron have been used as matrix materials and materials like TiC, SiC, B_4C, WC, Cr_3C, TiO_2, ZrO_2, Gr, MoS_2, and Si_3N_4 have been used as reinforcements to synthesize metal matrix composites. When compare P/M with other manufacturing methods, it offers ordered microstructure with improved physical, mechanical and tribological properties. From these, powder metallurgy could be commented as an extremely active and cost-effective method when compare with other process. This paper explains the selection suitable process parameters for synthesize MMCs using P/M technique. This paper made an attempt to present the mechanical and tribological properties of various composites fabricated through powder metallurgy technique.

Keywords: powder metallurgy, composites, mechanical properties, tribological properties, microstructure.

1. Introduction

Powder metallurgy technique is an easiest and suitable way to fabricate MMCs with several advantages such as uniform distribution of reinforcements in matrix requirement of less temperature when compared to other melting methods and cost effective one [1]. The powder metallurgy technique is widespread familiar because intricate shapes with precise sizes and shapes can be produced at high production rate in a cost effective manner [2]. In P/M process, the combination of elemental or pre-alloyed powders are compressed in a die and sintered in a furnace to bond the particles. Dissimilar varieties of ceramic materials are widely used to reinforce into aluminium alloy matrixes due to their behaviors such as refractoriness, high hardness, wear resistance, etc [3]. Components with challenging dimension and high strength components can be easily manufactured by the P/M method [4]. By following, the powder metallurgy manufacturing route magnesium matrix composites are being fabricated successively in a simple and cost effective manner [5]. Narayanasamy et al synthesized and studied the workability behavior of A-Fe composites during cold upsetting and concluded that for lower iron content greater fracture strain is attained and for higher iron formability stress index value increased [6]. Ravichandran et al. studied the forming behavior of AMCS prepared through powder metallurgy method and reported that reinforcement additions on matrix material decreases the densification and deformation properties due to matrix work hardening [7]. An effort has been made to synthesis W–Y and W–Y_2O_3 composites through powder metallurgy route and their mechanical properties and its microstructure have been reported by battabya [8]. Sivasankaran et al studied the flowability and compressibility of AA 6061−TiO_2 composites fabricated via powder metallurgy route [9].

2. Historical background

In general, components are produced to desired dimensions by machining, casting, hot working and cold working process. But occasionally metals and non-metals cannot be mixed and impossible to fabricate components with desired properties. The aforesaid drawbacks can be overcome by a method called powder metallurgy. In this method, metal and non-metal powders can be easily synthesized and blended together in a right proportion [10]. The blended powder is forced into a die to get desired dimension. Then it is toughened by sintering. After sintering, secondary finishing process is carried out and finally component with required properties, shape and size is achieved as shown in Fig. 1.

3. Powder metallurgy process

Many manufacturing methods are available to fabricate the ferrous and non-ferrous metal powders namely atomization, electrolytic deposition, chemical reduction and milling. Each manufacturing process possesses different advantages. The synthesized powders were formed into a desired size and shape by following the compaction process. After compaction, the billets are heated in a furnace for particular time and temperature to reduce the pores and to get high strength [10]. After the sintering process the parts can be directly used but some parts may require secondary finishing operation to reduce the stress.

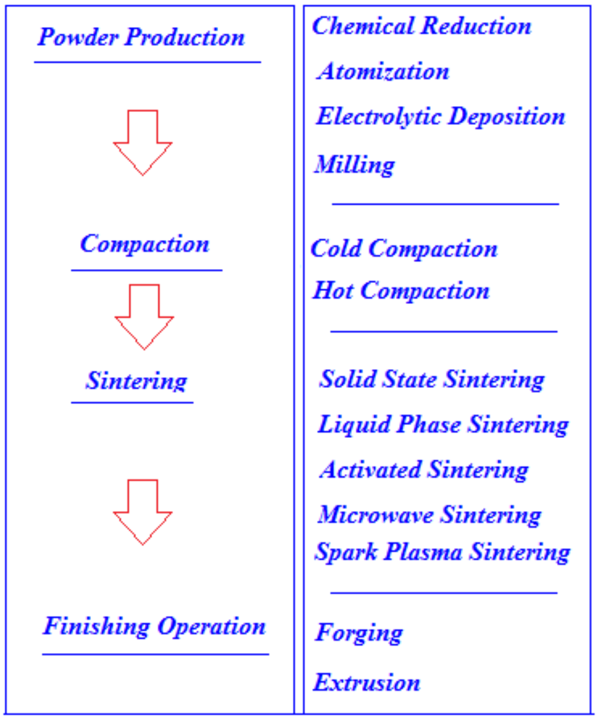

Figure 1 Powder metallurgy process

3.1. *Powder production*

In powder metallurgy process, powder is the raw material and it may be as pure elements, elemental blends or pre alloyed powders. Several methods are used to fabricate the powders. Atomization is the general method to produce powders due to its unique features. Stainless steel, nickel alloy and titanium alloy powder can be produced by atomization method. To produce other kind of powders like iron, copper, tungsten and molybdenum chemical reduction is the suitable method. Similarly iron, copper and silver powders can also be fabricated by electrolysis technique [10].

3.2. *Blending*

Blending is the method in which powders of the equal minimal composition but having various particle sizes and shapes are combined. To achieve homogenous distribution of particle sizes and to reduce the porosity blending should be done [4, 10].

3.3. *Compaction*

Compaction of powder mixture is commonly conducted by using suitable punch and die to produce green compact using mechanical or hydraulic presses [10]. With the help of uniaxial press the powder mixtures were cold compacted at a suitable pressure [11]. Ravindran et al. used the uniaxial press to obtain AA2024-SiC-Gr green compact at a pressure of 845 Mpa [12].

3.4. *Sintering*

Sintering is the process of heating the green compacts in a furnace at a controlled atmosphere to tie the particles. Sintering process are conducted below its melting point in various furnaces such as mesh belt furnaces, walking beam furnaces, pusher type furnace and batch furnace [10]. It has been reported by many researchers that at maximum sintering temperature are used to produce the components with good surface finish and properties. The Al6061-TiC green compacts were sintered for 3 h at three different temperatures 723, 798 and 873 K and it was proved that when the sintering temperature gradually increases mechanical properties of the material was also increased [13]. Ravichandran et al. carried out the sintering process in an electric muffle furnace for the material Al-TiO_2 at a temperature range of 590^{o}C for a time period of 3 h [4].

3.5. *Finishing operation*

Sometimes the sintered parts may be exposed to finishing operations. Ravichandran et al. conducted the cold upsetting investigations on aluminium metal matrix composites and studied the densification and deformation of the preforms [1]. Workability studies were carried out on the Al-20% SiC powder metallurgy composites during cold upsetting. Due to better densification stress ratio parameter (σ_θ/σ_f) was greater for Al-SiC composites related to pure aluminium. Owing to fine pore size linked with high hydrostatic stress (σ_m), the stress ratio parameter (σ_θ/σ_f) was reduced for Al-SiC composites associated to pure aluminium [14]. A study has been undergone to estimate the strain hardening behavior practiced during the cold working of sintered aluminium–iron powder metallurgy composite performs during upsetting process in several stress state situations such as uniaxial, plane and triaxial [15].

4. Effect of process parameter in P/M

The selection process parameter is an important one in the powder metallurgy process. The compaction pressure, sintering time and sintering temperature are the major factors. The improved mechanical and tribological properties can be achieved by selecting the above mentioned factors properly. Ravichandran et al. made an investigation on process parameters to acquire maximum strength co-efficient in Al–10 Wt% MoO_3 composite followed by Taguchi L9 orthogonal array and reported that improved strength co-efficeint was achieved at maximum compaction pressure and at higher sintering temperature [18]. Suththa studied and reported that maximum green density was attained at maximum compaction pressure and at higher sintering temperature [17]. From the investigation it has been informed that suitable sintering temperature and time outcomes in enhanced wear properties of Al-Al_2O_3. At higher temperature porosity was reduced and densification was improved [18]. A study was carried out by Umasankar et al. AA6061-SiC on the mechanical properties like sintered density and micro hardness by the effect of process parameters and it was stated that compaction pressure have much influence when compare to sintering temperature [19].

Table 1 Effect of Process Parameter in P/M

Material	Compaction pressure (MPa)	Sintering temperature (^oC)	Sintering time (h)	Results
Al-10Wt%MoO_3 Composites	250 300 350	500 550 600	1 1.3 2	300 MPa, 600^{o}C, 1.3 h was acknowledged as optimal factor.
Al–Al_2O_3 Composites	440 440 440 440 440 440	600 600 600 500 550 600	0.45 1.05 1.30 0.45 0.45 0.45	550–600^{o}C, 0.45–1.05 h was identified as proper temperature and time.
AA6061-SiC Composites	350 450 550	400 500 600	1 2 3	550 MPa, 500^{o}C, 1 h was suggested as optimum parameter.

5. Influence of reinforcement on mechanical properties

Studying the mechanical properties of particulate reinforced metal matrix composite is a essential one. Hossein Abdizadeh et al investigated the mechanical properties of aluminium/zirconium powder metallurgic composites and reported that when increasing the reinforcement percentage, hardness was increased. But the yield and compressive strength value was decreased when reinforcement content was increased [20]. The influence of iron addition on mechanical properties of AMC was studied and witnessed that significant improvement in the mechanical properties such as hardness and compressive strength of Al-Fe composite was achieved because of intermetallic development [21]. Erdemir et al. studied the mechanical properties of functionally graded Al2024/SiC composites and it was confirmed that in the initial stage when adding SiC in 30% & 40% micro hardness was increased further increasing the SiC content more than 50% & 60% micro hardness value was reduced because of high porosity. Bending strength was also increased while adding 30 & 40% and on further increasing SiC to more than 40% slightly it was decreased. This was due to heterogeneous distribution between the matrix and reinforcement material [22]. An effort was made by Antony Vasantha Kumar et al. to study the effect of rutile (TiO_2) content on the wear and micro hardness characterization of aluminium based hybrid composites. The hybrid composites Al-15%SiC-12%TiO_2 shows substantial improvement in micro hardness [11]. Ravindran et al studied the hardness of Al2024-Gr-SiC composites fabricated via powder metallurgy route. Due to extraordinary hardness of SiC reinforcement and proper dispersion of SiC reinforcement in the composites, the hardness of the hybrid composite material was increased. The reason for increase in hardness was because of increased density [12]. Amigo et al Investigated the hardness of the Al–SiC & Al–SiC-Gr composites and reported that when adding the Graphite with the SiC & Al hardness value has been considerably reduced [27]. Rajkumar et al. [29] studied the hardness of Cu-TiC-Gr hybrid composites. From the experimental work it was witnessed that superior hardness achieved for hybrid composites. The reason for increase in hardness is due to the addition of TiC. Yusuf Abdullah [30] investigated the hardness of Al-B_4C composites and concluded that while increasing the 10% B_4C to pure Al the harness of the composites were increased. Ravichandran et al. [31] studied the mechanical properties of Al-TiO_2 hot extruded powder metallurgic composites. The result shows that addition of 5% TiO_2 leads to high tensile strength and 7.5% TiO_2 leads to high hardness. Mehdi Rahimian et al. examined the hardness of Al-Al2O3 composites and reported that addition of 15% Al_2O_3 reinforcement hints to increase in hardness [18].

Table 2 Influence of reinforcement on mechanical properties

Matrix Material	Reinforcement Materials	Composites	Mechanical Properties		Ref. No.
			Hardness	Ultimate Strength	
Aluminium	SiC & Gr	Al2024-5%Gr-20%SiC	63 BHN	-	12
Copper	TiC & Gr	Cu-15%TiC-5%Gr	98.8 VHN	-	29
Aluminium	B_4C	Al- 10%B_4C	81.7 VHN		30
Aluminium	TiO_2	Al- 5%TiO_2	-	98 MPa	31
		Al- 7.5%TiO_2	43 VHN	-	31
Aluminium	Al_2O_3	Al-15%Al_2O_3	156 VHN	-	18

6. Augmentation of reinforcement on tribological properties

Wear study includes the use of the principles of friction, lubrication and wear. Jeyasimman et al [13] investigated the dry sliding wear behavior of nano level and hybrid composites AA6061 reinforced with TiC and Al_2O_3 and reported that for nano composites wear rate increased while increasing load and sliding velocities. Minor wear rates and friction coefficients were found for hybrid (TiC-Al_2O_3) strengthened with AA6061 nanocomposites. Ganesh et al. [24] studied the consequence of sintering temperature on dry sliding wear behavior of Al2219 reinforced with SiC and concluded that at high weight percentage of SiC decreases the wear rate. Kanthavel et al. [25] studied the tribological properties of Al reinforced with Al_2O_3 & MoS_2 at different loads and speeds and concluded that, at a sliding distance of 1000 m, sliding speed of 1.5 m/s with applied load of 5 N, minimum wear loss and coefficient of friction was achieved. Anthony Vasantha Kumar et al. [11] investigated the wear behavior and micro hardness of Al−15%SiC & Al−15%SiC−x%TiO_2(x = 4, 8, 12) composites. The Al−SiC−TiO_2 hybrid composites achieved superior wear resistance and micro hardness when compared with Al−15%SiC. Fig. 2 (a) and (b) clearly shows the influence of sliding distance on friction Co-efficient of the various composites.

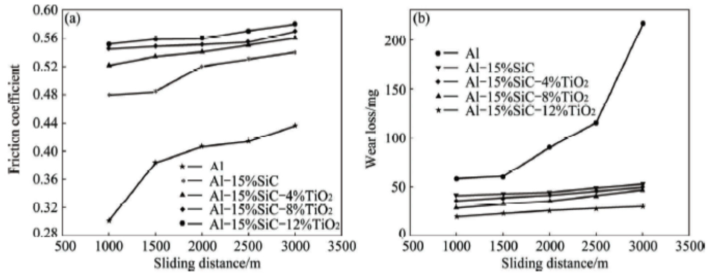

Figure 2 Effect of sliding distance on friction coefficient (a) and wear loss (b) of Al hybrid composites [11]

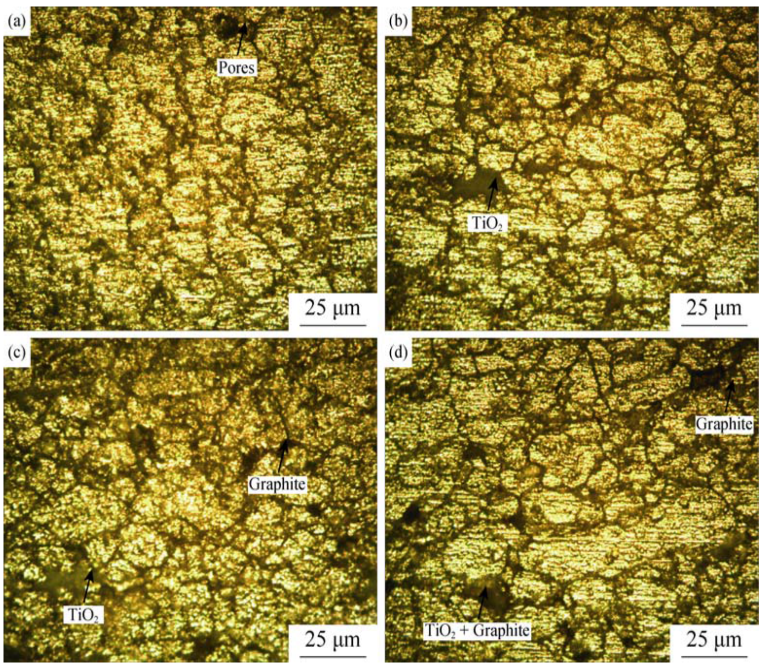

Figure 3 Microstructures of (a) Al-5%TiO_2-2%Gr (b) Al-5%TiO_2-4%Gr [6]

Selvam et al [26] studied dry sliding wear behavior on magnesium matrix reinforced with zinc oxide nano composites. The experiments were carried out at different loads and sliding velocities. At all three sliding velocities, wear rate was greater at greater load. When the coefficient of friction diminished as the sliding distance improved. Ravindran et al. [12] studied the tribological behavior of A2024-Gr composites and A2024-Gr-SiC composites. The tests were carried out under dry sliding settings and reported that A2024-Gr-SiC hybrid composites accomplished better wear loss when related with A2024-Gr composites. At higher load and sliding distance, low friction co-efficient and wear loss has been attained for hybrid composites.

7. Microstructural characterization of various composites

Ravichandran et al [6] carried out the microstructure investigation on as-sintered Al-TiO_2-Gr composites. The optical microscopic examination results definite that distribution between the reinforcement and matrix material was even. Fig. 3 (a) and (b) show the uniform dispersions of TiO_2 and Gr in Al matrix [6]. While adding 5% of TiO_2 to Al matrix very big pores were found. Jeyasiamman et al. [23] examine the microstructure of the AA 6061 nanocomposites reinforced by γ-Al_2O_3 nanoparticles. From the examination it is clear that addition of γ-Al_2O_3 nanoparticles to the matrix gradually condensed the size of the matrix. Aykut Canakci et al. [28] investigated the microstructure of SiC particles and Al powder influence on AA7075 chips. It was concluded that heterogeneous distribution was found while adding Al powders to the AA7075/Al–SiC composites.

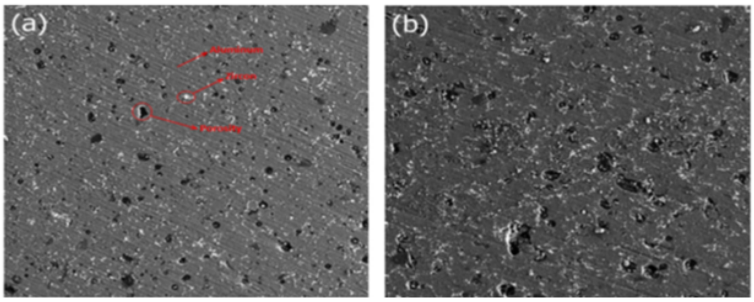

Figure 4 SEM Image of (a) Al-2.5%Zr (b) Al-3.5%Zr [20]

When adding SiC particle to the AA7075/Al–SiC composites partial dispersion was take place. Fathy et al. [21] examines the microstructure of the Al-Fe composites by using optical microscope. The results reveal that uniform distribution between the Fe and Al particle has taken place. Three types of phases, grain boundaries and particle accumulation are clearly visible in the micrographs. A study has been conducted to analyze the microstructure of Al-SiC-TiO_2 composites. The results displayed that proper bonding has been taken place between the Al matrix material and SiC, TiO_2 reinforcement material. The hard reinforcement SiC & TiO_2showed durable bonding to the Al matrix material [11]. Hossein Abdizadeh et al. [20]

examined the microstructure of aluminum/zircon composites and reported that increasing the zircon content of composites the uniformity and homogeneity of specimens decrease and zircon clusters tend to segregate. Fig. 4 (a) and (b) shows the micrographs of Zircon in Al matrix [20].

8. Conclusions

1. From the detailed literature survey, it was concluded that, powder metallurgy route is the easiest route to synthesis the metal matrix composites with hard and soft reinforcements when compared with the other manufacturing techniques namely stir casting, Centrifugal casting, Investment Casting etc.

2. Proper bonding between the matrix material and reinforcements will occur when the composites fabricated through powder metallurgy route.

3. From the study it has been observed that composites synthesized through powder metallurgy method provided improved mechanical and tribological properties.

4. This article will be helpful for the scholars and scientist who are working in the field of metal matrix composites through powder metallurgy process.

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