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A review on the influence of process parameters on powder metallurgy parts

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Abstract

The capability of powder metallurgy (PM) process to produce high quality components/parts is largely dependent on the control of process parameters. To obtain the desirable quality characteristics or properties in the produced part, an appropriate combination of process parameters is required. This paper presents a detailed review of powder metallurgy process parameters and their effects on a wide range of properties while developing a wide range of metallic and composites products. Key process parameters in this study include compaction pressure, sintering temperature, sintering time, sintering atmosphere, lubrication and reinforcement percentage volume. Their influence on physical properties, mechanical properties and microstructure of PM parts are extensively discussed. An extensive literature study as reported in this paper reveals that compaction pressure, sintering temperature, time and sintering atmosphere highly influence part density and strength, whereas part hardness and wear are greatly affected by hard ceramic reinforcement addition, compaction pressure, sintering temperature and time. Die wall lubrication greatly improve the physical, mechanical properties and microstructure of PM components compared to powder mass lubrication. It is observed that the powder metallurgy process conducted at optimum parameters produce quality products. This paper aims to facilitate researchers and scholars by providing a detail knowledge of PM process parameters and their effects, for them to conduct research and development to establish the field further.

Keywords: Composites, Mechanical properties, Microstructure, Powder metallurgy

1. Introduction

The demand for high-quality products for automobiles, biomedicine, and other engineering applications has ensured the continued growth of the powder metallurgy (PM) industry. Due to its flexibility, environmental friendliness and excellent process control, this processing technology is most suitable for producing high density and high strength-to weight components [1-4]. Parts made of metallic alloys and composites have been manufactured through the PM process. Examples include; surgical implants, tungsten filaments for incandescent lamp bulbs, oil-impregnated bearings and gears, connecting rods, piston rings, gears, cams, bushings, bearings, and cutting tools [2, 5]. PM is one of the solid processing routes developed to overcome the problems associated with other fabrication methods. It is well suited for advanced processing, a vital requirement for high-performance, cost-effective products for the present-day global competitive market [6]. PM uses metallic powder to produce parts; it maximizes the use of materials and can be used to transform metals that seem impossible by other fabrication and processing techniques. Sources of powder are metals and ceramics. The most commonly used metals are aluminum, steel, iron, magnesium, and copper, while widely used ceramics are Al_2O_3, TiC, SiC, B_4C, WC, and fly ash [7-9]. The process can be designed to produce net shape or near-net shape components/parts. In near-net-shape, secondary operations such as machining, finishing, or grinding are necessary to improve dimensional accuracy, appearance, and surface finish, etc. Some of the advantages of the PM process include controlled microstructure, uniform distribution of powder particles, and little or no interfacial reaction [10]. Some of the limitations include not being suitable for parts with large and complex geometry. This is because the flow property of metallic powder restricts the complexity of part shape. Most PM products are simple and weigh less than 3.0 kg, but parts that weigh as much as 40 kg can be produced. It is also not suitable for low volume production due to the high setup cost. It is preferable for medium to mass production of parts [11].

The basic steps involved in a PM process are (i) powder mixing/blending (ii) powder compaction and (iii) sintering of green compacts (Figure 1). Each operation has unique parameters which can be controlled to obtain the best property of the part. Powder mixing involves the mingling of different powders to achieve homogeneity. This prepares the powder for compaction. During mixing, magnesium can be added in a small amount to serve as a binder [12] and wax or zinc stearate as a lubricant to reduce friction during compaction. Die wall lubrication improves the properties and microstructure of PM parts compared to powder lubrication [13, 14]. Powders with mixed particle sizes reduce porosity compared to powder with uniform particle size [15, 16]. An accurate combination of powder particle sizes is essential for improved microstructure and mechanical properties.

Applied compaction pressure transforms the loose powder into a solid mass to form the required shape. It can be performed cold or warm [17-19], and pressure applied may be in a uniaxial or biaxial direction [20, 21]. Conventional compaction can be modified

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into isostatic pressing, where parts can be produced in a flexible mould using pressure applied from all directions. Components made from hot isostatic pressing exhibited higher density, mechanical strength and improved microstructure [22-24].

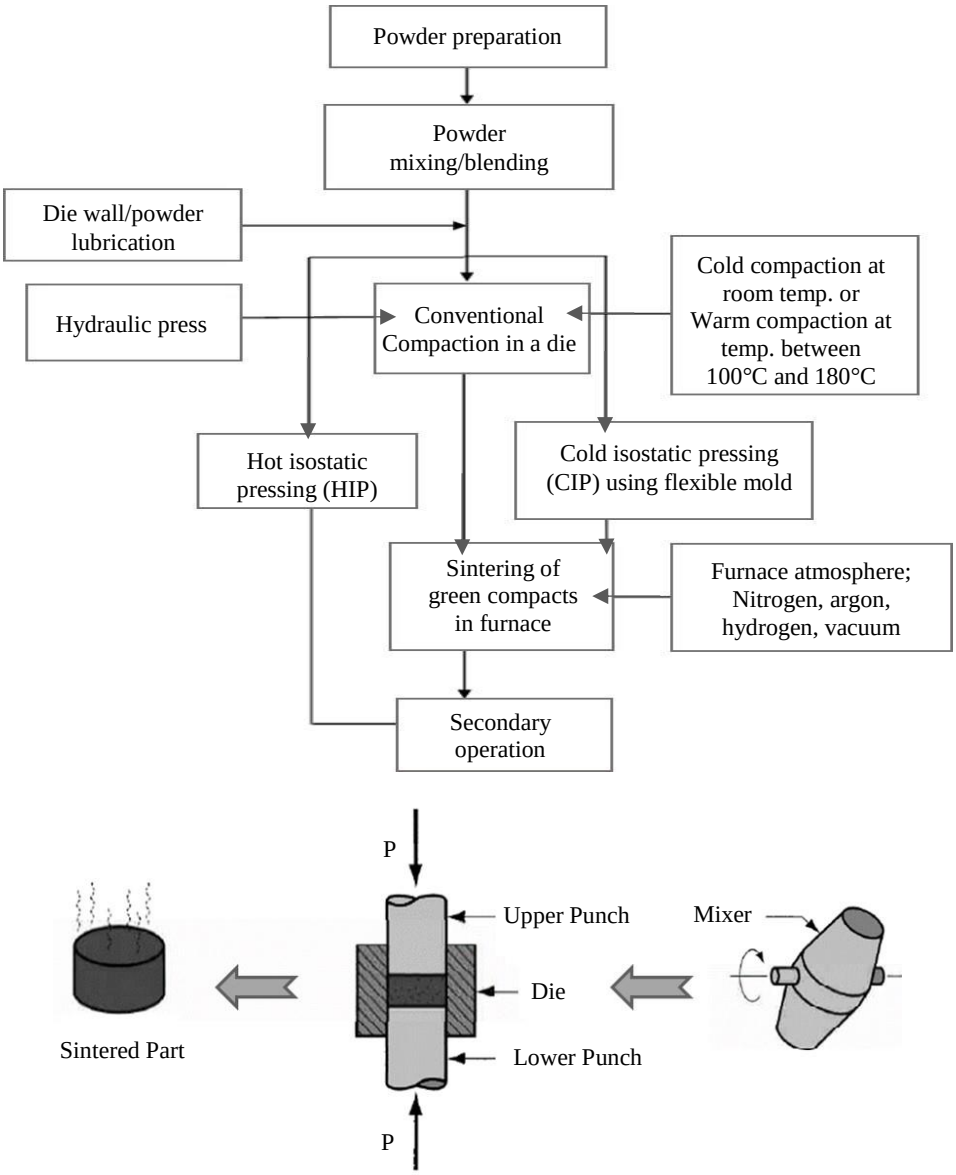

Figure 1 Illustration of powder metallurgy process

Sintering increases the density and strength of the green compact and eliminate lubricants and binders used during mixing and compaction. The heat applied during sintering causes solid-state bonding of powder particles. An increase in sintering temperature and time increases metallic powder particle diffusion, followed by part shrinkage resulting in pore size reduction and denser structure [25]. During sintering, there is a need to control the furnace atmosphere to prevent the contamination of PM parts and improve quality. Widely used furnace atmosphere are nitrogen, hydrogen, argon, and vacuum furnace atmosphere.

Process parameters significantly influenced the physical properties, mechanical properties and microstructure of PM parts. The effects of these parameters such as compaction pressure, sintering temperature, time and atmosphere, lubrication, particle size and reinforcement percentage volume on density, strength, hardness and wear have been extensively investigated [26-28]. Most research focus in PM has been on increasing the density and improving the microstructure of PM parts which ultimately increases mechanical properties. According to Li et al [26], Bardhan et al [29], PM compact density depends on compaction pressure, sintering temperature and powder type. Pani and Khuntia [30] observed that the surface smoothness of PM compacts increases with a rise in compaction pressure and temperature.

This review investigates the process parameters and performance of the PM method to produce metallic and composites parts. The influences of processing parameters such as compaction pressure, sintering temperature, time and atmosphere, reinforcement volume, etc., on density, porosity, mechanical properties, and microstructures have been reviewed and discussed. Effects of Optimal processing parameters on the overall quality of PM components are also highlighted.

2. Powder metallurgy process parameters

The quality of PM components is dependent on the control of process parameters. Several parameters have been identified as factors that can influence the outcome of PM products. Parameters such as milling time, compaction pressure, compaction temperature, compaction duration, sintering temperature, sintering duration, sintering atmosphere, lubricant concentration, reinforcement

concentration and powder particle size, and their effects on product quality have been widely investigated [31-36]. For instance, Stalin [37], Umasankar [38] reported that compacting pressure and reinforcement concentration influenced density and hardness significantly. Leszczyńska-Madej [39] observed that the tribological properties of metal matrix composites were greatly enhanced by sintering temperature and hard ceramic addition. Table 1 shows workable ranges of some PM parameters used for different studies. It will facilitate the selection of process parameters for future work.

Table 1 A summary of ranges of powder metallurgy process parameters used by different researchers

Materials	PM process parameters							Ref
	Comp. pressure P_c (MPa)	Comp. Temp. (^{o} C)	Particle size (P_s) µm	Sintering temp (T_s) (^{o}C)	Sintering time (t_s) (min)	Optimal T_s, t_s	Sintering Atmosphere	
Al-GNP composites.	600	RT	8-15	550-630	60-300	630, 180	vacuum	[25]
Al/SiC/B4C	150	RT	-	610	15	-	Nitrogen	[40]
Al/zircon	440	CIP	-	600-650	65	650, 65	Argon	[41]
Al alloy/ fly ash	200-515	RT	20/150	575-625	90	-	Nitrogen, vacuum	[20]
Al/Mg	489	28-150	122 /144	400-460	60	-	Argon	[18]
Cu-Re	350-650	100-160	-	300-900	60-180	-	Argon	[42]
Iron powder	400-850	RT	5, 45, 63, 80nm	500-1120	20-30	900, 20	Vacuum, Nitrogen	[36]
Al-Al2O3	440	RT	30/ 3, 12, 48	500-600	30-90	600, 45	Argon	[27]
Cu/graphite	700	RT		900	60	-	Argon	[43]
Al/fly ash	414	RT	70-106	600-645	30-360	-	Nitrogen	[44]
Al/Pb/fly-ash	200-400	RT	-	500-590	45	-	Argon	[10]
AA6061/SiC	350-550	RT		400-600	60-180	-	Nitrogen	[38]
Al/xGnP	500	RT	-	400-600	300	-	-	[35]
MWCNTs/Al	30	RT	20-40nm/25	500-650	120-360	590, 240	Argon, Vacuum	[26]
6711Al/SiC	400	RT		570-630	60	630, 60	Vacuum	[45]
316L stainlesssteel	800	RT		1300	30	-	Nitrogen, Argon	[46]
Iron powder ASC 10.29	400	120-180	20-180	900-990	30	990, 30	Argon	[47]
Al/SiC	300	RT	63/40-60	580-620	60	620, 60	Nitrogen	[39]
AA6061/SiC	350-550	RT	35	400-600	60-180	-	Nitrogen	[38]
Al6061/SiC/Gr	250-750	RT	-	620-630	60	-	Nitrogen	[48]
AISI 316L stainless steel	600	RT	-	1200-1400	60	-	Hydrogen	[49]
Mg/SiC	125	RT	-	465	60	-	Argon	[32]
Mg/TiC/MoS2	740	RT		530	60	-	-	[50]
Mg/WC/Gr	200	RT	50	500	60	-	-	[51]
Mg/SiC	650	RT	-	500-670	30	-	-	[52]
Cu/Co/Mo	600	RT	44/1.8/44	1000	30	-	-	[53]
Cu/WC/SiC	45KN	-	<80/49	870-984	90	-	-	[54]
Ti alloy (Ti-6Al-4Zr-0.5Mo-0.6Si)	200	CIP	-	1300	240	-	Vacuum	[55]
Al/MoO_3	200-300	RT	-	400-600	60-180		-	[37]
Cu matrix composites	550-650	-		800-900	60-90	800-900, 60-90	-	[56]

RT-Room Temperature, CIP-Cold Isostatic Pressing

2.1 Powder particle size distribution and mixing

According to Prem Prakash Seth [31], particle shapes and sizes significantly enhance PM parts' mechanical properties and microstructure. Some of the unique shapes include triangular, spherical, irregular, etc. [57-59]. Commonly used powder particle sizes are in the micro-scale i.e.,~(1-200µm) and currently the nano-scale i.e.,~(1-200nm) is also in application [32, 60]. Generally, powder with fine particle sizes produces parts with high density, enhanced microstructure and mechanical properties compared to larger particle sizes. A correct combination of powder particle sizes reduces porosity and significantly improves microstructure and mechanical properties [15, 36]. Powder with mixed particle sizes perform better than powder with uniform distribution [22, 61]. For example, a mixture of particle size of 20µm Al7075 (matrix) and 20wt% 120µm Al_2O_3 (reinforcement) produced composite with the highest density, hardness and compressive strength [15].

Powder mixing/milling is the first step in the PM processing sequence and it is performed using a ball mill. Milling of powder particles results in a homogeneous mixture, preventing agglomeration, a significant problem associated with powder processing [62]. Generally, As percentage reinforcement/alloying volume increases, particle clustering increases. A recent study by Ponhan et al [32] observed that a more homogeneous powder mixture was achieved even at a higher volume fraction of reinforcements at a longer milling time using a ball mill. The use of ball milling during PM can be said to achieve two significant purposes; firstly, to ensure homogeneity of the powder mixture and secondly to break down powder particles into more acceptable sizes. This ultimately results in higher mechanical properties and improved microstructure. This finding is consistent with previous investigations [63, 64].

In an earlier study, Wang et al. [65] used a two-step processing method to improve the homogenous distribution of reinforcing particulates over the magnesium matrix. Microstructural characterization of the magnesium composites showed a homogeneous distribution of the particulates over the matrix, but with increased porosity.

During milling, a control agent such as alcohol is added to the powder mixture to prevent agglomeration [27]. For ease of mixing, the container should be less than 90% capacity [40, 43, 66]. For higher efficiency of mixing, appropriate selection of mixing parameters is necessary. Commonly used milling parameters are mixing speed, mixing time and ball-to-powder weight ratio (BPR). The mixing speed should be within the range of ~(150-200) rpm and the mixing/milling time should be long enough for the powder particles to attain uniformity to prevent particle clustering [48, 67].

2.2 Powder compaction and lubrication

Powder mixtures are compacted in a die cavity using a punch to form green compact. The compaction pressure transforms the loose metallic powder into rigid mass to form shape. As the applied pressure increases, powder particle consolidation increases such that certain degree of cold welding occurs [18, 19, 68]. The green compact should have high density and strength to prevent breakage during ejection. When the actual or measured density is almost equal to theoretical density i.e. relative density (RD) close to 100%, it means that sufficient compaction has been performed, as density increases porosity decreases [61, 69].

Compaction can be performed cold or warm [70]. Cold compaction is performed at room temperature. In warm compaction, the die or powder mixture is heated to a suitable temperature usually below 200^{o}C before the application of pressure. The different compaction temperature used by different authors are shown in Table 1. Xiao et al [19], compared the effect of cold and warm compaction on the properties of PM parts. Results reveal that green density and strength were higher with warm compaction. This finding is consistent with other investigations [42, 66]. The applied compaction pressure not only enabled the shaping of green compact but also to overcome friction between metal particles and die wall. Friction causes density variation and pressure loss during powder compaction [21]. To increase the effectiveness of the applied pressure, the use of lubricants is recommended [67]. Base powder types, lubricant types and concentration are key considerations during lubrication, their effects can significantly impact on product quality [71, 72]. Several lubricants have been used for PM studies, they include: zinc stearate (or) stearic acid, lithium stearate, mixture of silicon fluid and graphite powder, ethylene bis-stearamide (EBS), polystyrene wax, and paraffin wax [73, 74].

The use of lubricant for powder compaction offers both advantages and limitations. The advantages include: (i). prevention of die wall friction, (ii). minimization of interparticle friction (iii). prevention of density variation, (iv). improvement in the flow properties of powder particles (v). easy ejection of green compacts, and (vi). prevention of tool wear. The major limitation is the reduction in density and mechanical properties of sintered compacts for lubricant mixed with powder mass. Lubricants can be applied either on the die walls or admixed with the metallic powder mass. Studies conducted to investigate the effects of lubrication on the physical and mechanical properties of PM parts revealed that parts with die wall lubrication exhibited higher density and mechanical properties compared to parts produced from powder mixed with lubricants [75, 76]. For higher physical and mechanical properties of PM products, no lubricants should be added to the powder mass [21]. In the case where the use of lubricant on the powder mass is unavoidable a low melting lubricant with optimal concentration should be used [71, 77]. Optimal lubricant concentration improves product quality, but excess lubrication can have a deleterious effect on microstructure. High lubricant concentration in the powder mass can obstruct particle to particle contact necessary for strong bonding as well as create problem of overly protracted burnout time to remove the lubricant from the sintered compact. When the lubricant is eventually burnt out, it creates micro-voids in the microstructure which results in poor mechanical properties of the final products [77]. Lubricant concentration less or equal to 0.5wt% has been recommended for optimal performance [78, 79].

2.3 Sintering temperature, time and atmosphere

To further consolidate on the properties of green compacts, they are subjected to heat treatment known as sintering. During sintering, the grains of the green compacts get welded together at a temperature usually below the melting point of the matrix metal to form stronger bond. Notable properties that can be affected by sintering include density, volume, strength, hardness etc. [20, 26].

Temperature, time and furnace atmosphere are important sintering parameters that can impact on the quality of PM parts [25, 80]. To obtain the highest density and mechanical properties, sintering temperature and time should be optimized. Too low or too high sintering temperature and too short or too long sintering time may cause grain growth and weak interparticle bond which can undermine the properties of final product [57, 81]. Table 1 shows the different sintering temperature, time and furnace atmosphere used for different studies.

Most sintering processes are solid phase sintering where the powder constituent remains solid throughout the heat treatment process. However, there are instances where the melting point of one of the powder constituents is far below that of the matrix metal. At high temperature, the metal particles with lower melting point melt while the rest constituents remain solid. The melted metal wets other solid particles to form a strong bond with a dense structure. Padmavathi et al [45] observed that during the sintering of 6711Al-SiC composite compacts, a liquid phase of AlMg2Si was formed at 586^{o}C before attaining the sintering temperature of 630^{o}C. Furthermore, during sintering of Al/Pb/10 wt% fly-ash composite compact, Reddy et al [10] noted that at the temperature range of 500^{o}C-560^{o}C, a liquid phase was formed due to the melting of Pb. Beyond 590^{o}C solid aluminum particle diffusion was prevalent, resulting in a denser structure. Liquid phase sintering enhances microstructure and consequently physical and mechanical properties of PM parts. However, caution must be taken to prevent chemical reactions that may result in the formation of undesirable chemical compounds.

During sintering, the furnace atmosphere is expected to be controlled. The need for a controlled furnace atmosphere is to prevent material contamination and enhance microstructure and mechanical properties. Studies have shown that gases such as argon, nitrogen, hydrogen etc. can be used to control the furnace atmosphere [39, 49, 82]. A vacuum furnace atmosphere is also an effective furnace atmosphere for sintering. Materials such as tungsten carbide (WC), stainless steel etc. have been sintered using a vacuum furnace atmosphere [80]. Naci Kurgan [46], Xue et al [83] used argon and nitrogen gas as sintering furnace atmospheres for their studies. It was found that the specimen sintered in nitrogen furnace atmosphere showed higher physical and mechanical properties compared to specimen sintered in argon furnace atmosphere.

3. Effects of process parameters

3.1 On density and porosity

High density PM compact is a result of little or no pore spaces in the powder particle arrangement. Density is significantly influenced by compaction pressure, sintering temperature, time, lubrication and reinforcement concentration [84-86]. Porosity in PM compacts is assumed eliminated when the sintered density equals the theoretical density. This cannot be practically achieved due to the efficiency of the PM process. Porosity increases due to inadequate milling time, compaction pressure, sintering temperature, and sintering time. Particle clustering adversely affects the physical/mechanical properties and microstructure of PM parts. Therefore proper milling is essential for enhanced properties (see Figure 2). Other factors that may increase porosity in PM compacts are lubrication, particle size distribution and percentage reinforcement volume [25, 44, 87]. The relationship between particle packing density and porosity can be explained further using equation (1)

$$\rho + \phi = 1.0 \quad (1)$$

Where,

ρ is the particle packing density, and ϕ is the porosity.

An increase in compaction pressure increases the particle packing density. When ρ is equal to one, it means porosity is zero, and measured density equals theoretical density [15, 61]. In an investigation on the effect of compaction load and particle size on porosity of aluminum alloy compact, the lowest porosity was at a higher compaction load and mixed particle size distribution, i.e. (25µm+100µ). Reports have it that powder with assorted particle sizes are less porous than powder with uniform particle sizes.

Iron compact with die wall lubrication, sintered at 1300°C exhibited higher density compared to iron compact with powder lubrication. Diffusion rate and pore shrinkages increased as sintering temperature and time increased, resulting in a denser structure [35]. Furthermore, Gokçe and Fındık [88] compared the green and sintered density of Al-Mg compact prepared from powder with and without admixed lubricant. Aluminum compacts without admixed lubricant gave the highest density.

The use of ceramic reinforcement increases porosity in metal matrix composites. This may be due to the porous nature of ceramic materials. As the percentage volume reinforcement increases, porosity increases [87, 89]. Porosity in Al/Gr/SiC composites significantly increased when the percentage volume of SiC reinforcement was above 10%. This finding is consistent with the studies of Venkatesh and Harish [90] and Padmavathi et al. [45].

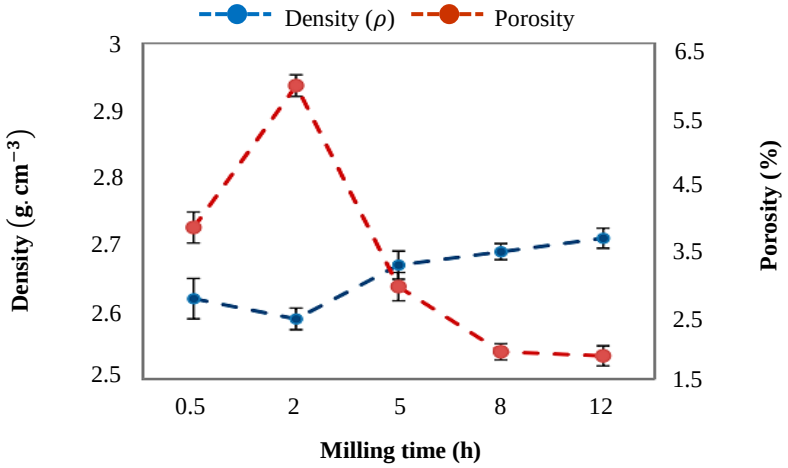

Figure 2 Effect of milling time on the density and porosity of Al/Al_2O_3 nanocomposites [91]

3.2 On strength and ductility

The porosity and strength of inter-particle bonds primarily influence PM parts' mechanical properties and microstructure. Effects of compaction pressure, sintering temperature, time and atmosphere, powder particle size, reinforcement concentration, and lubrication on strength and ductility of PM parts have been investigated [57, 92-94]. Increasing compaction pressure reduces pore spaces in powder particle arrangement by increasing particle-to-particle contact area, allowing cold welding to take place. Increasing sintering temperature increases the diffusion rate of metallic particles, thereby filling vacant positions. This results in a denser structure and consequently reduced porosity [95]. For example, GX40CrNiSi25-20 stainless steel compact sintered at 1300°C for 3hrs exhibited higher tensile strength compared to compacts sintered at 1200°C [82]. In another instance, increasing the sintering temperature of MWCNTs/Al compact from 590°C to 650°C, a sintering time of 4hrs, increased the tensile strength from 156MPa to 167MPa. Materials respond to sintering temperature and duration differently; this may be due to their chemical composition and phase characteristics. Rahman et al [47] reported that the strength of sintered iron compact, warm compacted at 180°C increased from 320MPa to 620MPa as the sintering temperature increased from 900°C to 990°C for a sintering duration of 30mins. Warm compaction reduces friction between powder particles and die wall and increases lubricant effectiveness [96]. Moreover, Rahimian et al. [27] reported that the ductility of Al-Al_2O_3 composites increased as the sintering temperature and time increased. The best value of ductility was at 600°C and 60 mins sintering time. Increasing sintering time from 60mins to 90mins had little or no effect on specimen sintered at 600°C. Low sintering temperature and time result in weak inter-particle bonds and ultimately low strength and ductility. Higher tensile strength can be achieved when lubricants are used on the die wall only. The use of lubricants on powder mass has not produced the best results notwithstanding, a concentration less than or equal to 0.5wt% has been recommended [88, 97].

The addition of ceramic reinforcement increases strength but decreases ductility. However, high volume reinforcement decreases both strength and ductility [56]. This is because of the inherent porosity and particle agglomeration associated with a high volume of ceramic reinforcement. According to Padmavathi et al [45], Prakash et al [98], Liu et al [99], the highest tensile strength recorded was at a percentage reinforcement volume of about ~10% for micro-size and much lesser for nano-size particles. In addition, fine particles perform better than coarse particles because they have fewer pore spaces than coarse particles. According to Rahimian et al [27], the best yield stress value for Al-Al_2O_3 composites was at a sintering temperature of 600°C and particle size less than 10µm. Hassani et al. [59] reported that a reduction in particle size from 16 to 12 µm caused a decreased porosity by 3.7%, increasing tensile strength and ductility.

The concentration of furnace atmosphere can impact strength and ductility of PM parts. More so, some furnace atmospheres are more effective than others. Butkovic et al. [82] and Kurgan [46] reported that Compacts sintered in nitrogen atmosphere exhibited higher strength but reduced ductility. In contrast, compacts sintered in hydrogen and argon showed higher ductility but reduced strength. More investigations are needed in this area to substantiate this finding further.

3.3 On hardness

Metals and alloys can be made harder for tailored application, especially for the production of cutting tools. The addition of Ceramic materials such as SiC, B_4C, Al_2O_3, and WC, to metal matrices and the optimization of processing parameters such as milling time, compaction pressure, sintering temperature, time, etc., increase hardness [90, 100-102]. As illustrated in Figure 3, hardness of Al/Al_2O_3 composite increases as the milling time increases. Homogeneous distribution of reinforcing/alloying particulates over the matrix can be achieved through milling, which results in an increase in hardness. Ravi Kumar et al [51], reported a significant increase in the hardness of magnesium composite on the addition of tungsten carbide and graphite. However, tungsten carbide had more substantial effect than graphite. Gurbuz et al [25] reported the highest hardness value of sintered Al/GNP composite at a temperature of 630°C, sintering time of 3hrs and reinforcement percentage volume of 1wt%. In a similar study, Latief et al [35] observed that the hardness of Al/GNP composite sintered at 600^{0}C for 5hrs increases as the GNP reinforcement addition increases up to 5wt%. The different hardness values obtained may be due to the variation in processing parameters, chemical composition and purity of phases. In a critical study [27, 23], the highest hardness value for sintered Al-Al_2O_3 composite was at a sintering temperature of 600°C. Higher temperature promotes faster diffusion of metallic particles, faster neck growth to form stronger inter-particle bonds. Furthermore**,** reports show that the highest hardness value of Al/Al_2O_3 composites was with particle size less than 10µm and a percentage reinforcement volume of 20wt% [67, 48]. Other examples of particle sizes used that have produced superior hardness include 30µm [101], (20µm+120µm) [15] etc. PM parts developed using fine powder particles perform better than parts produced using coarse particles. However fine powder particles require higher compaction pressure to achieve high green density and hardness [36]. Coarse particle sizes are easier to deform as compaction pressure increases, resulting in increased porosity. The addition of ceramic reinforcement such as Al_2O_3 to aluminum matrix increases hardness, this is because Al_2O_3 is naturally harder than aluminum. As the percentage reinforcement volume increases (≤ 20wt%), hardness increases [103]. Another reason for increased hardness is the strengthening mechanism of ceramic materials. The addition of ceramic material to metal matrix impedes dislocation motion, and this increases hardness.

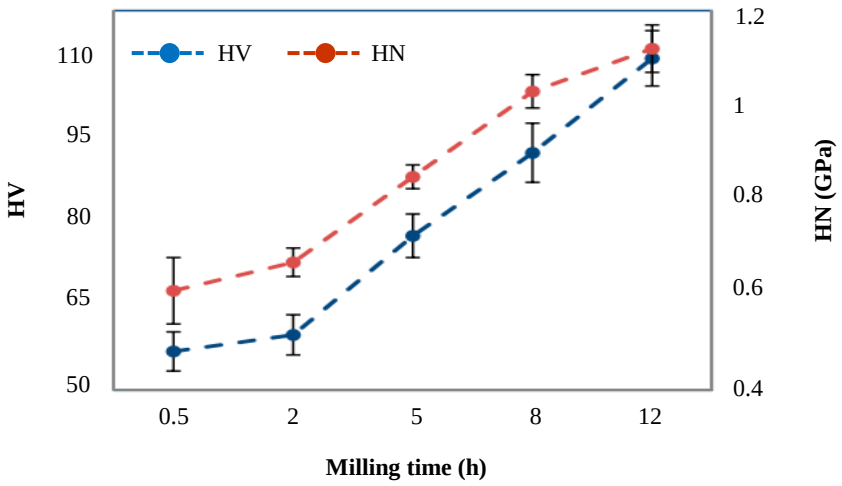

Figure 3 Effect of milling time on micro-hardness (HV) and nano-hardness (HN) of Al/Al_2O_3 composites [91].

A critical study reveals that the stainless-steel compact sintered in nitrogen furnace atmosphere exhibited improved hardness than the stainless steel compact sintered in argon [46]. Nitrogen gas can form nitride, and the nitride formed impacts microstructure by decreasing pore spaces. This ultimately increases density and hardness.

3.4 On wear characteristics

Wear of surfaces which is a common phenomenon associated with mating parts in relative motion is undesirable. The occurrence of wear causes failures of machine elements that results in material loss. Hardened materials tend to have higher wear resistance than softer materials. The wear properties of PM parts can be enhanced by the addition of hard ceramic reinforcement such as TiC, B_4C, SiC, n-ZrO2, and the optimization of processing parameters such as sintering temperature, time, and reinforcement concentration [104, 62, 50, 39]. Rahimian et al [67] discovered that the wear rate of Al/Al_2O_3 composite increased by 7% when the sintering temperature increased from 550°C to 600°C after a sintering time of 45 mins. But an increase of 22% was observed when the sintering time increased from 45mins to 90mins. Besides increasing wear rate by 22%, an increase in grain area from 820µm to 1723µm was also observed. Excess sintering time causes grain growth (increase in grain area), resulting in reduced hardness and increased wear rate. Some studies

discovered that the use of hybrid reinforcements such as (Gr+MoS2), (TiC+MoS2) resulted in an improvement in the tribological properties of magnesium composites [105, 50]. However, molybdenum disulfide (MoS_2) reinforcement was more effective in reducing wear loss in magnesium composites when compared to graphite reinforcement.

In the wear mechanism of Al/Al_2O_3 composites, the dominant material removal modes are abrasion, adhesion, and delamination, contingent upon the applied load and sliding velocity [106]. Furthermore, a study by Diler et al [23] to investigate the effect of particle size and reinforcement volume on the wear rate of Al/SiC composites discovered that the highest wear resistance was at a particle size of 91μm and a reinforcement volume of 15wt%.

3.5 On fracture behaviour

Generally, the fracture modes of pure metals are ductile, with surfaces characterized by small dimples. At low sintering temperature and high percentage volume reinforcement addition, porosity of sintered compact increases while ductility reduces. The effect of this on fracture behaviour is a ductile-brittle fracture mode [22, 26]. Leszczyńska-Madej [39] observed that the fractography of sintered aluminum at various temperatures revealed elongated small dimple colonies as evidence of ductile fracture. However, sintering at a temperature of 620^{o}C was sufficient to form a stronger inter-particle bond thereby reducing porosity.

In a critical study investigating the effect of sintering atmosphere on fracture behaviour, Naci Kurgan [46] observed that coalescence of pores was more in the ductile fracture surface of 316L stainless steel compacts sintered in argon atmosphere than those sintered in nitrogen atmosphere under the same processing condition.

3.6 On microstructure

Microstructural characterization of sintered compacts is quite essential for the determination of microstructural features. Attributes such as micro and macro porosity, pore size, particle size, shape and distribution, phase structure etc. can be determined using optical microscope, scanning electron microscope equipped with EDS (SEM-EDS) and X-ray diffractometer (XRD). Before microstructural examination is performed, the surface of the compacts is polished and after which etched by Keller's reagent. However, etching process is not compulsory [20, 25, 88].

The influence of processing parameters on the microstructure of PM parts has been extensively investigated [41, 46, 57, 82]. Improved microstructure of PM parts is a function of homogenous distribution of the reinforcing/alloying phase over the matrix. As shown in Figures 4(a-b) and Figures 5(b-c), few pore spaces are seen on the microstructure of the aluminum composite due to the homogenous distribution of SiC and Al_2O_3 reinforcement over the aluminum matrix respectively. XRD pattern analysis of Figure 4(d) indicates interfacial compound in the microstructure. This occurs at higher sintering temperature and longer sintering time [39, 67, 107]. Figure 5a shows the uniform distribution of Si into Al matrix, whereas Figure 5d illustrates the occurrence of pores etc. when the reinforcement reaches 10wt% [108].

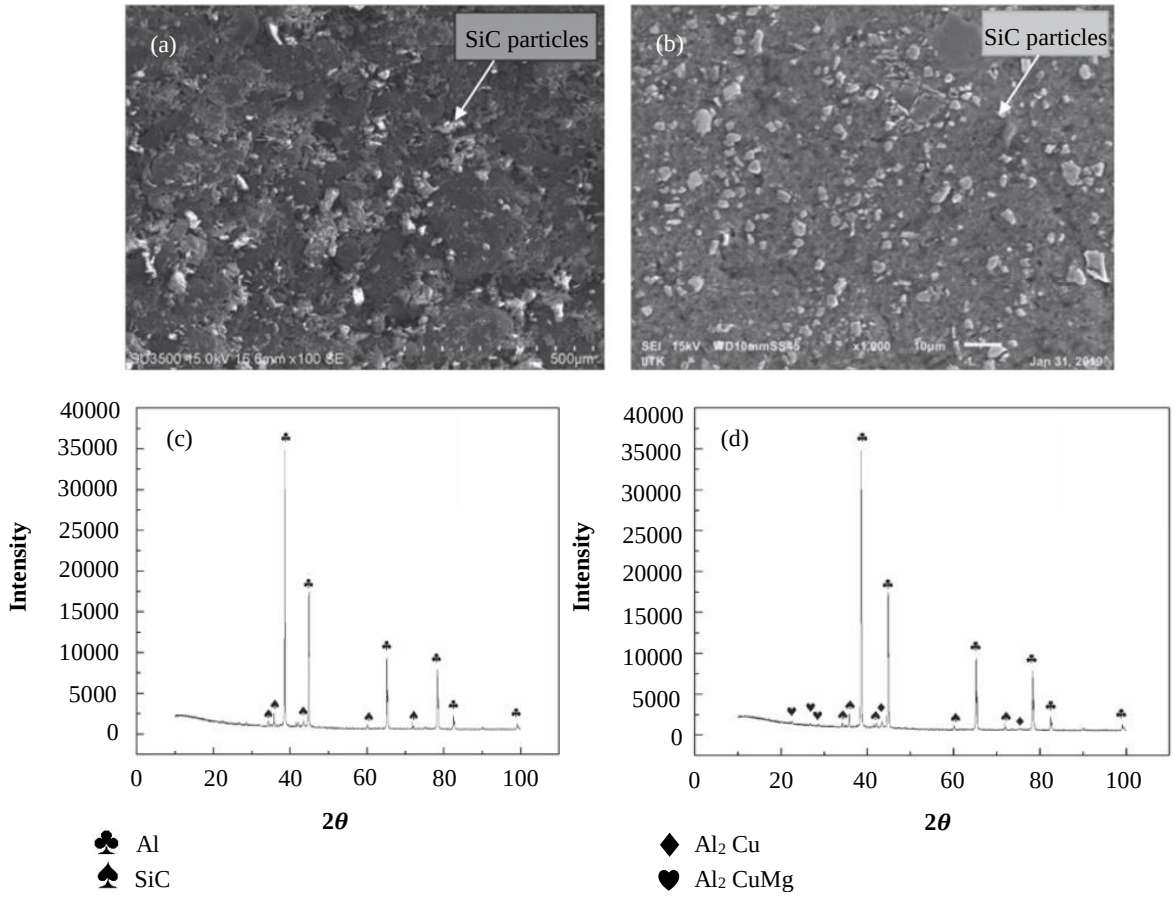

Figure 4 Microstructure of Al-Cu-Si-Mg/SiC. (a) 5wt% SiC (b) 10wt%SiC. XRD pattern of Al composite (c) 5wt% SiC (d)10wt% SiC [109].

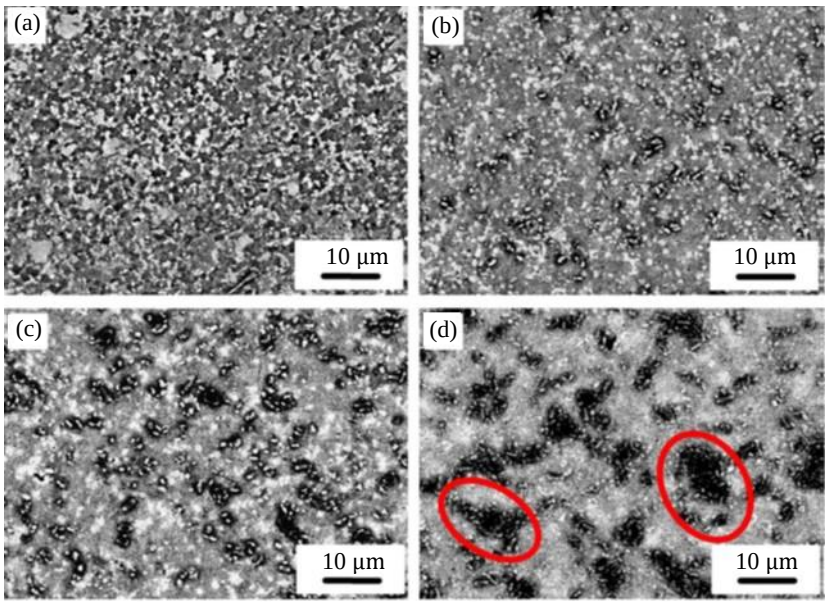

Figure 5 SEM Micrographs of Al-12Si/Al2O3 composites with (a) 0wt%, (b) 2wt%, (c) 5wt% (d) 10 wt% reinforcements [108]

As reported by Li et al [26], an increase in sintering time from 4hrs to 6hrs for Al/MWCNT composite specimen sintered at 590ºC, resulted in the formation of Al_4C_3 brittle compound. Al_4C_3 compound is undesirable because it can degrade the mechanical properties of composites. In another study by Dhanashekar et al [104], Padmavathi et al [45], it was observed that Al_4C_3 interfacial compound was not found in the phase structure of Al/SiC composites sintered for 1hr. The reason for this may be due to optimal sintering time of 1hr. Longer sintering time causes a chemical reaction between material phases, resulting in inter-facial compound in the microstructure. Another reason may be that the XRD has poor sensitivity and as such could not detect the presence of Al_4C_3.

4. Conclusion

After careful review of several studies on powder metallurgy, its process parameters and their effects, the following conclusion can be drawn. As an established production process, powder metallurgy is most suitable for the production of metallic and metal matrix composites parts. The metals commonly used for powder metallurgy are aluminum, steels, magnesium and copper. PM processing parameters that can significantly influence product outcome include milling time, compaction pressure, sintering temperature, sintering time, furnace atmosphere, lubrication, powder particle size and reinforcement concentration. Due to excellent process control, powder metallurgy components are characterized by little porosity, higher density, refined microstructure and enhanced mechanical properties. Comparatively, Powder metallurgy products are superior to as cast products. For best values of density, strength, hardness and wear resistance, lubrication should be performed on the die wall only. In the case of powder mass lubrication, the lubricant concentration should be less than 0.5wt%. For composite production, the reinforcement percentage volume should be ≤10wt% for the best value of strength and ≤20wt% for the best value of hardness and wear resistance. Formation of deleterious compound like Al_4C_3 can be prevented if the sintering temperature and time are not excessive.

In PM process, selection of processing parameter values is dependent on the properties of base metals. For aluminum powder, compaction pressure of (150-650) MPa, sintering temperature of (400ºC-650ºC) and sintering time of (15-360) mins have been used. For iron and steel powder, compaction pressure of (400-850) MPa, sintering temperature of (900ºC-1400ºC) and sintering time of (20-60) mins have been used. For Magnesium powder, compaction pressure of (125-740) MPa, sintering temperature of (400-670) ºC, and sintering time of (30-60) mins have been used. For copper powder, compaction pressure of (200-800) MPa, sintering temperature of (300-000) ºC, and sintering time of (30-180) mins have been used.

Sintering furnace atmosphere plays a critical role in PM process and as such should be well controlled. Property variations of sintered parts may be caused by sintering gas concentration in the furnace. More so, some sintering gases are more effective than others. More studies should be conducted to investigate the effectiveness of sintering gases in relation to base metal powder.

5. References

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