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Review on Using Powder Metallurgy Method for Production of Metal-Based Nanocomposites

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Abstract

Due to the constant need for metal matrix nanocomposites (MMNCs), which are used in industrial applications such as automotive, aerospace, and many others, and therefore many researchers, are interested in making them nanocomposites with better performance, studies are continuing to improve their properties. In contrast to other versatile conventional production methods, powder metallurgy (PM) method is highly effective in eliminating porosity, wetting and casting defects. In this review, an in-depth discussion of the different MMNCs fabricated by the PM method with an explanation of the different stages of preparation of these nanocomposites such as powder production, pressing and sintering was discussed. Also, the different factors affecting milling and sintering processes were reviewed. Finally, the advantages, disadvantages, and more common applications of PM in the preparation of these nanocomposites mentioned above were discussed in some detail.

Keywords: Powder metallurgy; Nanocomposites; Metal matrix nanocomposites; Sintering; Milling parameters; Applications.

Introduction

Recently, many technological problems have been solved, thanks to composite materials. From this perspective, more attention has been given since 1960 to the use of polymeric- or metal-based composites in the industrial field. These desirable composite materials can be easily produced by combining two or more materials to give a unique set of properties [1-3]. It is extremely important to note that the basic concept of composite is that it contains matrix materials that include metals, ceramics or polymers. On the other hand, reinforcements include fibers, particulates or whiskers [4, 5].

The method chosen to prepare nanocomposites depends heavily on the properties of the matrix along with its influence on the properties of the reinforcements. Besides this, another major consideration for selecting and manufacturing nanocomposites is their chemical inertness and non-reactivity. It is possible to classify nanocomposites according to the type of matrix as shown in Fig. 1.

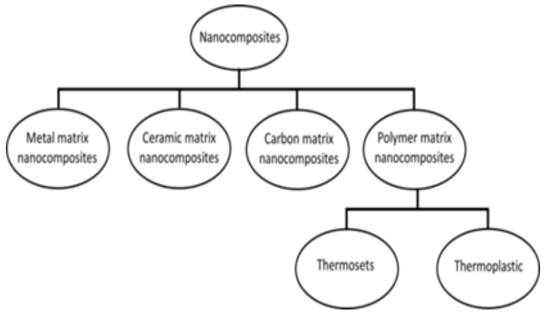

Fig.1. Classification of nanocomposites on basis of matrix

Metal-Matrix Nanocomposites (MMNCs)

Metal matrix nanocomposites reinforced with particles or fibers are known to play a significant role as structural building materials. Furthermore, the aerospace, defense, and automotive industries mainly depend on ceramic phase reinforced MMNCs [6-9]. These composite materials have several promising properties arising from the combination of the physical and mechanical properties of metals represented by high ductility, good fracture toughness, excellent thermal conductivity, and excellent ceramic properties represented by high modulus of elasticity and high strength. Generally,

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the high hardness values for nanocomposite materials can be significantly enhanced by the presence of high volume fraction of reinforcement agent. Therefore, MMCs exhibit many favorable properties such as high specific strength, excellent stiffness and good wear resistance [10-12]. These composites can be prepared by using ductile material (aluminum, copper, titanium, or nickel as the matrix material) [13-17] and ceramic reinforcements (e.g., alumina, zirconia, silicon carbide, or graphene) [18-23]. It is important to highlight that the final characteristics of nanocomposites are strongly correlated to the following factors:

(1) The properties of the matrix.
(2) The type, shape, dimensions, geometric arrangement and volume fraction of the reinforcement.
(3) The wettability at the interface or the bonding between the reinforcement and matrix, and presence or absence of voids.

It is important to stress that the volume fraction of the reinforcement and the bonding at the interface have strong role to play as they are greatly correlated to the strength, ductility, elastic modulus, and wear resistance of the nanocomposite [6].

Powder Metallurgy (PM)

It is well-established that pressing metal powders into a specific shape is not a modern technology. This sentence is confirmed by the traces of ancient civilizations in prehistoric times such as iron column in Delhi, and some precious Egyptian tools and artifacts made of metals [24, 25]. In general, PM is a well-established industrial technology for producing nanocomposites [26-29] and nanobiocomposites [30-34] made by heating pressed powders below their melting points and impossible to obtain it from melting.

Advantages of PM

In fact, there are many reasons for choosing PM as the preferred method for producing nanocomposites. These reasons include [35-37]:

- The parts produced are clean, bright and ready for use.
- The possibility of mixing some materials those are impossible to mix, such as mixing metals with ceramics.
- Ease of automation compared to other manufacturing processes.
- Facilitating the manufacture of materials or nanocomposites that may be impractical or impossible with other processes such as fraction materials, cemented carbides, diamond cutting and electrical contact materials
- Manufacturing of nanocomposites with very high melting points.
- A wide range of composites allowed.
- The product composition can be controlled effectively.
- Manufacture of nanocomposites with controlled levels of porosity and thus can be used in various applications.
- Its cost-effectiveness for mass production due to absence of labor cost, additional manufacturing cost, etc.

Disadvantages of PM

1. Powder metallurgy adopts high-cost equipment, so this method is only economical for mass production.
2. Complex design is difficult to produce due to less metal powder flow capacity.
3. The final produced have limited ductility.
4. The difficulty of the sintering process is the low melting powder.
5. The impossibility of having a completely dense product.

The Different Processing Stages of PM

Generally, the process of producing composites using the PM method involves a set of technologies that process raw materials in powder form to manufacture components of various types [38]. These techniques include the following steps:

Production of Composites Powder

The first step in the PM process begins with the preparation of the nanocomposite powder by the mechanical alloying method. Mechanical alloying (MA) is process that depends on the occurrence of solid-state processing between powder surfaces of the reactants at room temperature. Accordingly, it can be extensively utilized to produce alloys, metal matrix composites or ceramic matrix composite those cannot be produced by conventional methods. Furthermore, it is considered as an efficient method to produce nano-sized composites [39, 40]. Additionally, it provides homogeneous distribution of fine reinforcing particles and work hardening. The repeated welding, fracturing and rewelding of powder particles lead to intimate mixing of the reactants on an atomic scale and lead to the formation of stable and metastable supersaturated solid solutions, crystalline and quasi-crystalline intermediate phases, as well as amorphous phases [41, 42].

Mechanism of Alloying

In metal-matrix composites, ductile-brittle system, fine and homogeneous dispersion of brittle phase occurs in the ductile matrix by MA process. The scheme of MA process of this system is illustrated by Fig. 2. The first stage of milling is characterized by the occurrence of deformation and fragmentation for ductile and brittle particles, respectively. Subsequently, ductile particles begin to weld and the brittle ones come between two or more ductile particles at the instant of the ball collision [15, 43]. The formation of real composite particles is obtained by placing the fragmented reinforcement particles in the interfacial boundaries of the welded metal particles. It is important to mention that the welding is the dominant mechanism in this process and consequently, the particles vary their morphology by piling up the laminar particles. The above mentioned phenomena, i.e. deformation, welding and solid dispersion are responsible for significant increases in the fracture process. Furthermore, they cause equiaxed morphology. Then, both welding and fracture mechanisms reach the equilibrium causing the formation of composite particles with randomly orientated interfacial boundaries. When steady state is reached, the microstructure becomes greatly fine and optical microscope is no longer able to identify the interfacial boundaries [44, 45].

Processing Variables in Milling

MA is considered as a complex process that requires optimization of many process variables to get the desirable product, microstructure and/or properties. Notably, the nature as well as the composition of the powder mix is not considered here as a variable. These will decide the nature of the phase formed (solid solution, intermetallic, or amorphous phase, etc.) in the milled powder [42]. For a given composition of the powder, there are some vital parameters those greatly affect the final constitution of the milled powder and can be summarized as the followings:

Raw Materials

The raw materials those frequently used for MA process is commercially pure powders taking on the account that the particle size is not considered as crucial factor as it exponentially decreases during milling process with time [46].

Types of Mills

There are various types of milling equipments those available for MA of powders. These types differ in their capacities, operation speed and efficiency of milling.

SPEX Shaker Mills

SPEX mills are considered as shaker ones those able to mill about 10-20 g of the powder at a time. They are usually used for laboratory as well as alloy screening purposes. The typical SPEX shaker mill is shown in Fig. 3. It consists of one vial containing the powder specimen and grinding balls. These balls are secured in the clamp and swung energetically back and forth several thousand times a minute. The back-and-forth shaking motion is combined with lateral movements of the ends of the vial, so that the vial appears to be describing a figure of 8 or infinity symbol as it moves. With each swing of the vial the balls impact against the sample and the end vial, both milling and mixing the sample. Since the amplitude of the clamp motion is about 50 mm and its speed is about 1200 rpm, the ban velocities are high (on the order of 5 m/s). Therefore, the force of the ball's impact is great. Accordingly, these mills are high-energy variety [42, 47].

Planetary Mills

This type of mills is widely used for the preparation of bulk powders. The high output of milled powders is considered as the main advantage of this mill type. The typical planetary mill is shown in Fig. 4. In this mill, the rotation of the base plate leads to the rotation of vials in a planetary motion around their axes. It is worth to mention that the powders are ground by the action of centrifugal force of the balls. This mill is characterized by the presence of four milling vials and each one can accommodate up to 250 g of powder mixture. On the contrary to SPEX mills, this type is considered as a low energy mill where its vials are larger in size and capacity and consequently, the transmitted energy is much lower than SPEX [48, 49].

Attritor Mills

As illustrated in Fig. 5(a,b), this mill type is basically consists of a vertical drum containing a series of impellers. The latter promote the ball charge to mill the particles.

Due to the collisions between balls and vial wall, and between balls, agitator shaft, and impellers, powder size is significantly reduced and become micron-sized. These mills are frequently used to mill large quantities of powders (from 0.5 to 40 kg). Since the velocity of the grinding medium in the attritors is lower than (about 250 rpm) that in the planetary or SPEX mills, its energy of milling is low [50].

Milling Time

The most important factor that greatly affects the milling is its time as it fulfils the steady state between the fracturing and cold welding of the powder particles. The required time highly depends on the mill type, the milling intensity, the ball-to-powder ratio and the milling temperature. Accordingly, the required milling time is chosen based on the combination of the former mentioned parameters and the specific powder system. Unfortunately, if the milling time is longer than required, contamination is highly expected and undesirable phases can be obtained. Instead, the time should be accurately adjusted to avoid these unfavourable effects [44, 51-54].

Ball-to-Powder Weight Ratio (BPR)

It is the ratio of the weight of the balls to the powder (BPR), also referred to as charge ratio (CR). The most common BPR for small capacity is 10:1. The milling time is strongly correlated with that ratio, i.e. if this ratio is high; the milling time is significantly reduced to achieve a specific constitution of the powder. This reduction in milling time is mainly attributed to that the high BPRs apply higher weight proportion of balls and consequently, the number of collisions per unit time is high. It is important to note that the used BPR should be accurately chosen based on the maximum capacity of milling vials. In most of the cases, to obtain the optimum results, the filling of the container should not exceed 50% of its volume while, the half of the vial space is left empty [55-57]. The effects of milling time and ball-to-powders weight ratios on particle size are shown in Fig 2.

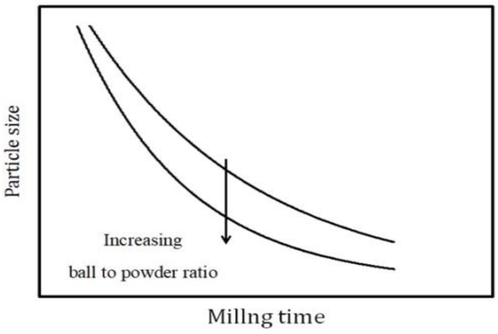

Fig. 2. A scheme showing the effects of milling time and ball-to-powders weight ratios (BPRs) on the particles sizes of the milled powders.

Milling Speed

Milling speed plays a significant role in MA process. This vital role is attributed to that the high speed refers to the high rate of energy transfer to the powders and consequently, the required time is reduced. On the other hand, the maximum speed should be limited in many cases. At high speed contributes to the sticking of balls to the walls of the vial and subsequently, the energy cannot be transferred to the powder particles. Therefore, the maximum speed should be also carefully adjusted lower than this critical value. It must be noted that the temperature of the system can be elevated at higher speeds which may accelerate the transformation process and contributes to the occurrence of the degeneration of solid solution or crystallization of amorphous phase [58, 59]. The Fig. 3 illustrates the movement of the correct and wrong balls during the milling process.

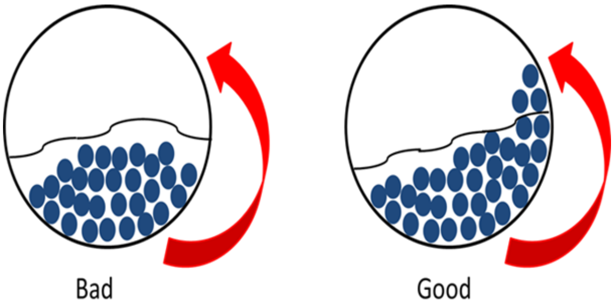

Fig. 3. Good and bad movement of balls during the milling process.

Milling Medium

There are many materials those can be broadly utilized as milling medium such as stainless steel, tungsten carbide and alumina. As a general consideration, the milling container as well as the balls is made of the same material to avoid any cross contamination of the powder. It is worth to note that both vial and balls should be properly selected. In order to create enough impact force on the powder, the density of the milling medium must be high enough. Moreover, the size of balls have strong role to play in energy transfer as the latter is significantly increased by the increasing of the size of balls. However, small balls encourage the formation of metastable phase. In case of the Al-Al_2O_3 system, various sizes of balls were utilized to get higher collision energies. It is well-known that the different ball sizes greatly reduce the amount of cold welding of the powders on the surface of the balls and the internal surface of the vial. The main reason for this is attributed to high shear forces developed between the balls of different sizes that tend to detach the powder coatings from the surface of the balls [42, 60].

Process Control Agent

In order to avoid any undesirable and excessive cold welding of the powder particles onto the internal surfaces of the grinding medium during heavy plastic deformation, a process control agent (PCA) is essential. It is also known as lubricant or surfactant. Frequently, about 1-1.7 wt.% of stearic acid is used as PCA during MA process. The advantages of using PCA can be summarized in minimizing the effect of cold welding due to its adsorption onto the surface of powder particles and accordingly, the agglomeration is considerably reduced. However, the weight proportion of PCA to powder should be above the critical value otherwise, the powder particles size tend to increase as the PCA helps to reduce the surface tension of solid materials [45, 61].

Powder Compaction

Another step in powder processing is the compaction where it forms the loose powders into required shapes with adequate strength to resist until sintering is finished. Basing on this principle, compaction process is achieved by applying pressure on the particles to compose cohesion among them. This is usually termed as the green strength [62, 63]. It is interesting to discuss that the compaction process effectively promote the followings [64]:

1. The reduction of voids those found between the powder particles and consequently; improve the density of the consolidated powder (Fig. 4).
2. Enhancing the green strength in the consolidated powder particles by bonding.
3. Encouraging the sintering process by enhancing the contact area among the powder particles (Fig. 5).

Compaction is performed by applying pressure on the milled powders those poured into the die cavity. In order to enhance pressure homogeneity and decrease the porosity in the compacted body, the compressive forces should be applied on the top or both the top and the bottom sides

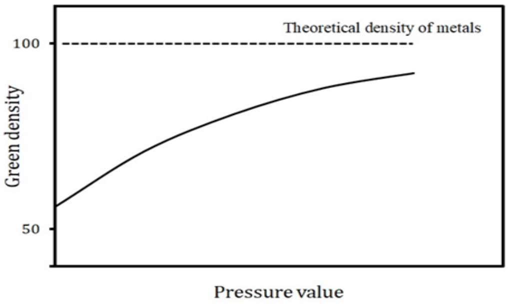

Fig. 4. A scheme showing the relationship between pressure of compact and the density of powder compact.

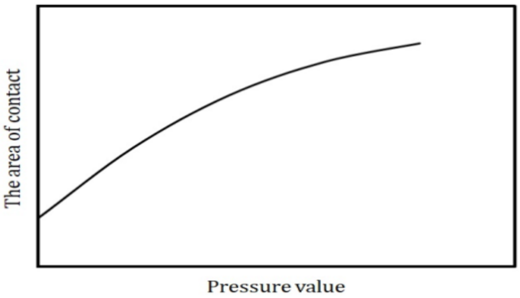

Fig. 5. A scheme showing the relationship between compaction pressure and contact area of powder compact.

Sintering of the Compacted Powder

The heating of the compacted powder at a particular temperature, on the condition that it below the melting temperature of the main powder particles and above the required temperature that permits the diffusion between the neighboring particles, is referred to sintering. It is important to stress that sintering greatly helps to facilitate the bonding between the power particles and consequently, the strength of the final product is effectively increased. Bearing in mind that sintering process is performed in controlled inert, reducing atmosphere or even in vacuum to avoid the oxidation of powders. Before the sintering process, the compacted powder possesses very low green strength. Both the nature and the strength of the bond between the particles are strongly influenced by the mechanism of diffusion and plastic flow of the powder particles, and evaporation of volatile material from the compacted preform [65-68].

Solid State Sintering

This is the commonly occurring consolidation of metal and alloy powders. In this, densification occurs mainly because of atomic diffusion in solid state. Generally, there are three stages for solid state sintering [69-73]:

(1) Necks which arise at the contact limits between the particles and gradually grow. Furthermore, the pores are interconnected and their shapes are irregular.

(2) This stage is characterized by sufficient neck growth and the pore channels become more cylindrical in nature. Faster sintering is happened for smaller neck size as the curvature gradients is high. However, the pores become rounded after sufficient time at the sintering temperature. The neck growth is responsible for significant decrease in the curvature gradient and sintering which means that the pore volume is not changed. On the other hand, the pore shape is changed (become spherical and isolated) and persist to form a connected phase throughout the compact.

(3) This stage is characterized by the absence of any changes in porosity keeping the small pores even after long sintering times.

Factors Affecting Sintering Process

The most important factors affecting the sintering process can be summarized as the followings (Fig. 6) [24, 67, 71].

Process Variants

Sintering temperature

Both rate and magnitude of changes occur during sintering process are strongly increased by increasing sintering temperature.

Sintering time

It is well-established that the sintering degree is affected by sintering time. However, this factor has less pronounced effect than that induced by the sintering temperature.

Sintering atmosphere

In order to obtain the desired results, the production, use and control of sintering temperature should be carefully adjusted.

Material Variants

Particle size

Generally, reducing particle sizes contributes to enhancing sinterability, i.e. the greater pore/solid interfacial area can be obtained in the case of smaller particle size which produces a greater driving force for sintering process.

Particle shape

Particle shape can greatly encourage the sintering process as it may lead to better intimate contact between particles as well as increased internal surface area.

Green density

When the green density is low, the amount of internal surface area is significantly increased and therefore, greater driving force for sintering process is obtained. The steps to prepare the metal matrix nanocomposites using the powder metallurgy method are shown in Fig. 7.

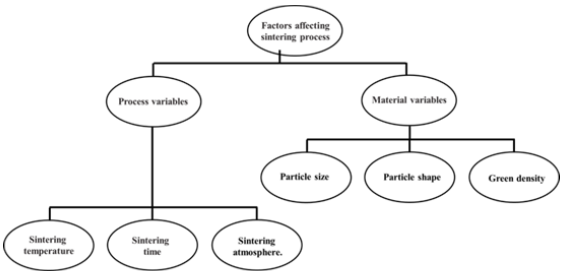

Fig. 6. Factors affecting the sintering process

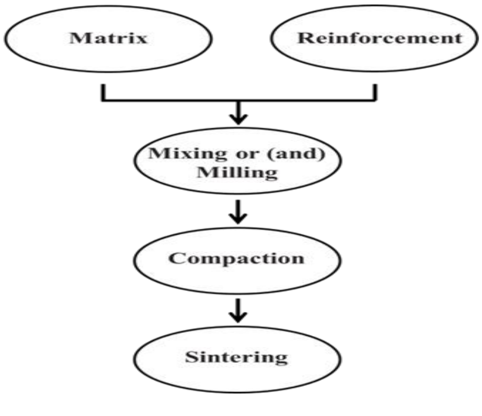

Fig. 7. A scheme of basic steps in PM process

Applications of PM

With the help of PM method, different metal-based composites can be easily produced to be used in different industrial sectors. The applications of this successful method can be summarized as follows [74]:

- Production of porous nanocomposites
- Loader Babbitt bearing for automobiles.
- Production of automotive oil pump gears.
- The production of refractory metal nanocomposites, for example: tungsten, molybdenum and tantalum for the manufacture of tungsten wires for filament in the manufacture of lamps.
- Production of cutting tools, wire drawing, dies and deep drawing dies.
- Production of electrical contract materials, for example: circuit breakers, relays, and resistance welding electrodes.
- Production of small parts of the product in automotive and instrumental applications where it provides the ability to produce an almost finished form requiring minimal automation, a strong economic advantage.
- Parts for vacuum cleaners, refrigerators, parts for guns, sewing machines.

Conclusions

Metal-matrix nanocomposites (MMNCs) are an interesting class of materials that have numerous uses in the fields of science and engineering. Several methods are available for preparing MMNCs. It is worth noting that powder metallurgy (PM) has attracted a lot of interest and inspired many research interests due to its promising results, wide potential applications, and potential scientific values. Several parameters and conditions have a significant effect on the process of preparing MMNCs in this way, either in the powder preparation stage or in the sintering process.

Conflicts of interest

There are no conflicts to declare.

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