Chapter 2

POWDER METALLURGY OF STAINLESS STEEL: STATE-OF-THE ART, CHALLENGES, AND DEVELOPMENT

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ABSTRACT

Stainless steels, a class of ferrous alloys, are well-known for their superior durability and their notable resistance to corrosion and creep. In recent decades, there has been an increasing demand for powder metallurgy components composed of stainless steel alloys for a variety of applications, including in the aerospace, automotive, chemical processing, and biomedical industries. Hence, significant research is being undertaken on these alloys. As such, an understanding of the required processing parameters and their optimization is essential to produce components with appropriate properties and extend the use of the economically valuable powder metallurgy technology to an increasing number of applications. This chapter discusses a range of powder metallurgy techniques that are currently employed for the processing of alloys, and in particular, stainless steel. Finally, the microstructures and properties of the components prepared by these techniques are also discussed along with their applications.

Keywords: Powder metallurgy; Sintering; Powder compaction; Microstructure; Mechanical properties; Corrosion

INTRODUCTION

The use of powder metallurgy (commonly abbreviated as PM) in the manufacture of metal components such as gears has grown in recent years. Traditionally, components

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produced by PM were pressed and then sintered in a dry hydrogen atmosphere to prevent oxidation of the fine powders [1]. Generally, relatively high sintering temperatures and prolonged sintering times are required, thereby rendering this process time consuming and uneconomical. However, studies by North American laboratories in the 1930s and 1940s paved the way for the commercial production of PM stainless steel components by the end of the 1940s [2–8]. Since then, the production and use of PM stainless steel components has been steadily increasing. Despite the fact that stainless steel components produced by PM are subjected to harsh conditions (i.e., requiring protective atmospheres and high temperatures), the PM industry is working to optimize the process conditions to ultimately improve the properties of PM stainless steel components. Indeed, the use of PM in the manufacture of stainless steel components for applications in the biomedical, automobile, aerospace, and chemical processing industries, among others, has been one of the factors driving this growth [6]. Various studies have shown that the poor corrosion resistance behavior of PM stainless steel components is often a result of metallurgical defects resulting from unoptimized processing conditions [9–13]. Hence, the development of a thorough understanding of the various aspects associated with the processing of PM stainless steel components is of particular importance. In this context, this chapter aims to provide a comprehensive review of the various PM processing techniques, properties, and applications that have been reported to date for metal alloys, and in particular, for stainless steel. Although the fundamental PM theories for metals and alloys have remained unchanged over the last 50 years, there have been a number of recent developments in the compaction of powders using techniques such as thermal spraying and powder rolling. This chapter therefore places particular emphasis on the underlying principles governing PM, which are applicable to all metallic systems, and are key to appreciating the science and engineering behind the topic.

**METALLURGY AND ALLOY COMPOSITIONS**

Stainless steel is an alloy of iron that is generally identified by its superior resistance to corrosion and the formation of related stains (hence, its common name). Although the resistance of stainless steel to oxidation and creep at high temperatures is generally excellent compared to other alloys [2], this material is not completely stain-proof, especially under low oxygen or high salinity conditions, including environments with poor air circulation. This limitation requires that various alloy grades and surface finishes be used to tailor a material to suit specific operating environments. Typically, the excellent corrosion resistance of stainless steel is a result of a chromium-rich microstructure, where a minimum amount of 11% Cr is required to prevent chemical reactions such as rusting, especially in unpolluted atmospheres [2–4]. In general, only a few stainless steels contain >30% Cr, and Fe levels are generally <50%. Furthermore, the majority of these alloys achieve their stainless characteristics by forming an ultra-thin surface film of chromium-rich oxides. Thus, Figure 1 provides a useful summary of a range of stainless steel compositions and their corresponding properties (where the numbers refer to the alloy grades). As indicated in this figure, various elements are added to Fe to produce a given stainless steel product destined for a particular purpose, such as strengthening (Mn and N), corrosion resistance (Ni and Cr), precipitation hardening (Cu, Ti, and Al), machinability (S or Se), pitting resistance (Mo), and sensitization reduction (Nb
and/or Ta), among others [5]. As such, each particular case leads to a specific family of stainless steel alloys.

Generally, the composition of PM stainless steel is derived from the wide range of existing popular wrought stainless steels [7], where the maximum permissible carbon content is 0.08% [8]. However, it is important to note that a number of wrought stainless steels contain lower C contents (i.e., ~0.03%), and are categorized as L-grades [9] (also known as low-carbon stainless steel). This low carbon composition enhances the ductility of the stainless steel, thereby facilitating compaction and malleability to give different shapes [11, 12], while minimizing chromium carbide contents (and in turn minimizing sensitization when cooling from the sintering temperature) [11]. It is important to note that stainless steel components sintered in a nitrogen-containing environment will often contain thousands of parts per million of nitrogen [13], and hence, cannot be considered to be L-grade stainless steel. In addition, stainless steels sintered in environments that are not adequately de-lubricated (i.e., that contain organic compounds from sealing greases, etc.) may contain more than 0.03% carbon, and therefore, are also no longer considered L-grade steels [14].

![Figure 1. Compositions and corresponding properties of the different stainless steel families of alloys (Reproduced from ref. [6] with the permission of Universities Press).](image)

**Classification of stainless steels**

To understand the fundamentals of PM, it is important that the classification of stainless steels (i.e., both PM stainless steel and wrought steel) is well understood. Generally, stainless steels are classified into four major families based on their microstructure, i.e., duplex, ferritic, martensitic, and austenitic stainless steels [15]. While ferritic, martensitic, and austenitic steels are composed of unique microstructures, the duplex family is a hybrid of the
ferritic and austenitic phases [16]. The classification shown in Figure 1 is based on the influence of the microstructure on both the physical and metallurgical properties of the stainless steel alloys.

Typically, at room temperature, pure iron exists as the ferritic (α) body-centered cubic (BCC) structure. As the iron is heated to a temperature >1670 °F (>910 °C), it transforms into the austenitic (γ) face-centered cubic (FCC) structure [14]. When the iron is further heated to a temperature of 2552 °F (1400 °C), it transforms back to the BCC ferritic structure. This transformation results into two types of ferritic phases: alpha (α) ferrite and delta (δ) ferrite, which are formed at lower and higher temperatures, respectively.

It has been reported that alloying pure iron with increasing quantities of Cr (i.e., ≤7%) leads to a gradual decrease in the temperature of the ferrite (α) to austenite (γ) phase transition, as well as that for the reverse transition from austenite to ferrite [14]. If Cr is added in quantities >7%, the transformation temperature from the α to γ phases increases, while the reverse transition temperature is lowered. This behavior decreases the range of temperatures over which austenite is stable [17]. Further increasing the Cr content >13% renders the ferritic phase stable at all temperatures, as shown in the Fe-Cr phase diagram provided in Figure 2.

![Figure 2. The binary Fe-Cr phase diagram (Reproduced from ref. [18] with the permission of ASM International).](image)

As the addition of Cr tends to stabilize the ferrite phase of the alloy, it is known as a ferritizer or a ferrite-forming element [19]. Other alloying elements also promote the same behavior, including aluminum, silicon, tantalum, titanium, molybdenum, and niobium [15]. When an Fe-Cr alloy or pure Fe is further alloyed with Ni (with an FCC crystal structure), different behavior is observed; the addition of nickel promotes the ferrite to austenite phase transition, and the γ-phase and α + γ regions that are located below the γ-phase region (i.e., at lower temperatures) are expanded [20], as shown in Figure 2. Hence, when an Fe-Cr steel is
alloyed with nickel, it is possible to produce an Fe-Cr-Ni alloy with high amounts of chromium in the austenitic form over a wide range of temperatures, including at room temperature [21]. However, it is important to note that the phase present at room temperature cannot be predicted using the equilibrium phase diagrams of the Fe-Cr-Ni or Fe-Ni systems [22], as the Ni atoms gradually diffuse at a slow rate into the ferrous matrix. As such, the quantity of austenite actually present in the majority of Fe-Cr-Ni or Fe-Ni alloys is generally greater than the quantity indicated by the equilibrium diagram.

Selection Criteria for PM Stainless Steel

Three out of the four stainless steel families (i.e., martensitic, austenitic, and ferritic) can be manufactured through conventional PM processes [15]. The austenitic and ferritic families normally form the bulk of PM stainless steels, while the martensitic family is mainly chosen for applications where high wear resistance is required [23]. In general, the selection of an alloy for a particular application depends firstly on its corrosion resistance [24], and subsequently on other important factors, such as the alloy’s magnetic and thermal properties, resistance to creep and oxidation at high temperatures, mechanical properties, fabricability, and cost.

PRODUCTION OF STAINLESS STEEL POWDERS

The key to manufacturing high-quality stainless steel components using the PM technique is optimization of the fundamental properties of the powder, including the particle size distribution, particle morphology, and composition. Therefore, the aim of powder manufacturing is to ensure that the properties of the powder are well controlled [25] in the most economic and efficient way.

In general, the PM production process involves blending, compacting (where the powders are pressed into the desired shape), and sintering (heating to a temperature below the melting point to cause solid-state bonding of the particles and strengthening of the components). These steps are referred to as the primary operations in PM and are depicted schematically in Figure 3 [26]; these stages will be further discussed later in this chapter. In addition, secondary operations are often required to improve the dimensional accuracy and increase the density of the final product. Generally, the intended use of a powder defines its specific engineering requirements and properties such as formability, apparent density, compressibility, and green strength (i.e., the strength after shaping but before sintering) [27].

In addition, both the engineering requirements for powder preparation and the powder properties themselves tend to define the majority of the PM manufacturing process conditions [28]. For example, water atomization is employed in the manufacture of stainless steel powders that can be cold-pressed into a die, otherwise known as compacting grade powders [29]. Such water atomization results in the formation of irregularly-shaped powders, as shown in Figure 4(a). Furthermore, gas atomization is employed to produce stainless steel powders for use in consolidation through hot pressing or extrusion [27]. Generally, stainless steel
powders manufactured through gas atomization adopt a spherical morphology, as shown in Figure 4(b).

![Diagrams of PM production sequence](image)

Figure 3. Schematic representation of the conventional PM production sequence, showing the (1) blending, (2) compaction, and (3) sintering steps, where the images shown in row (a) illustrate the powder microstructure and relative density, and those in row (b) show the processing equipment (Reproduced from ref. [26] with the permission of John Wiley and Sons).

![SEM micrographs](image)

Figure 4. SEM micrographs of (a) the irregularly-shaped stainless steel powder particles produced by water atomization, and (b) the spherical stainless steel particles produced by gas atomization (Reproduced from ref. [14] with the permission of ASM International).

The cooling rate experienced by the particles during water atomization is generally higher than that during gas atomization; however, both methods are sufficient to produce high-quality powders without segregation (i.e., the enrichment of atoms, ions, or molecules at the microscopic region) and that exhibit homogenous microstructures [30]. The combination of such properties with the excellent consolidation properties of these powders (usually resulting
in full density components) thereby results in alloys offering superior formability, fatigue, and impact strengths than those that can be attained using wrought alloys [31].

In addition to gas and water atomization, stainless steel powders can also be produced using either centrifugal atomization or hybrid gas-water atomization. All four of these techniques produce stainless steel powders suitable for component formation using injection molding [32]. The most important powder properties for injection molding are particles exhibiting a nearly spherical shape and an ultra-fine particle size (i.e., <20 μm) [32]. The preservation of the fill density and particle shape during compaction and sintering are also of particular importance.

**Water Atomization**

Figure 5 shows a schematic representation of the basic parts of a water atomization system, namely a power unit, an induction furnace, a runner, a tundish, a nitrogen purge valve, an atomization tank, a high pressure water tank, a decant tank, and a vacuum dryer. High-frequency induction furnaces are commonly employed in the processing of stainless steel, as they operate via induction-stirring and enable the different alloying elements to be effectively mixed [33]. In addition to induction stirring, open-air melting is also undertaken. When the melt charge reaches 50–75 °C above the melting point of the alloy being processed (i.e., the pouring temperature of the melt charge), the furnace is tilted to allow the metal melt to flow into the tundish via the runner [34]. The metal then emerges as a well-defined stream, which is transported to the stainless steel atomization tank (purged continuously with nitrogen to prevent air leaking into the tank), where it is poured through a high-pressure water jet to form the metal powder [5]. This nitrogen atmosphere is used to adjust the carbon level through slow cooling, which results in softening of the powder during the annealing process, rendering it more compressible. The collected water and powder must then be filtered to remove the water, which is followed by drying of the alloy. In addition, reduced oxidation of the stainless steel particles can be achieved using a lower pouring (i.e., atomizing) temperature [35]. Although a lower pouring temperature is advantageous with respect to the oxidation process, care must be taken to optimize this temperature to avoid freezing of the metal at the tundish nozzle [31].

**Gas Atomization**

In contrast to water atomization, where melting is performed under air, during gas atomization, the melting operations are carried out under vacuum or in an inert atmosphere to prevent oxidation of the alloying elements [36]. Gas atomization systems are therefore designed in such a way that they allow dry collection of the powder.
Figure 5. Schematic representation of the main components of a water atomization system (Reproduced from ref. [32] with the permission of the American Society for Metals).

Figure 6 shows a schematic representation of a typical gas atomization system. Usually, the atomization tanks employed for gas atomization are tall (~6–10 m) to ensure complete solidification of the powder particles before collection at the bottom of the tank [14]. It is important to note that, for a horizontal system, the horizontal gas tanks serve the same purpose as the vertical tanks, although according to the literature, horizontal designs tend to be cheaper than vertical ones [14]. In addition, melting can be carried out under air for the gas atomization process, and it has been shown that the chemical composition of the powder is comparable to that of the melt, and that the oxygen content is particularly low (i.e., ~200 ppm) [37].

It should also be noted that, despite gas atomized powders being produced in low-oxygen and inert environments, they tend to bear surfaces enriched with high-oxygen-affinity compounds; however, these layers are usually very thin (i.e., a few atoms thick) [12]. The inclusion of shearing substances during consolidation can therefore remove such layers to facilitate bonding between the particles.

**Post-Processing Treatment of Atomized Powders**

Following atomization of the stainless steel powders, a number of post-processing treatments are required, including drying, screening, annealing, and lubrication. Each of these treatment methods will now be addressed in turn.
Figure 6. Schematic representation of a typical gas atomization system (Reproduced from ref. [40] with the permission of the Metal Powder Industries Federation).

**Drying:** Following water atomization, the fine powder particles suspended in the powder-water slurry are allowed to settle to the bottom of the atomizing tank, and the excess water is removed by decantation [14]. The remaining water is then removed by filtration, heat treatment, centrifugation, or a combination of these processes.

**Screening:** After drying, the powder is screened to remove any oversized particles (i.e., >100 mesh (149 μm) for compacted powder applications [14]). If the powder is to be employed in filtration applications (e.g., in porous filters), then screening is carried out to achieve the desired screen sizes [38].

**Annealing:** Atomized powders tend to contain hundreds of parts per million of both nitrogen and carbon, which may decrease the particle compressibility and green strength, although these factors can often be enhanced by annealing the powder. However, it is important to note that annealing is not effective when the carbon content is too low (i.e., 150–200 ppm) [14] as the powder is soft, and can be sintered into a cake at the annealing temperature. Nevertheless, this cake can be milled, thereby allowing the original flow rate, particle size distribution, and apparent density of the powder to be restored [39].

**Lubrication:** Prior to pressing, the metal powder is lubricated to reduce the friction between the die and the wall, and also to reduce wear during compaction. The most widely used lubricants for this application are ethylene-bis-stearamide (Acrawax C) and lithium stearate [14].
CHARACTERISTICS OF STAINLESS STEEL POWDERS

The distinctive characteristics of PM stainless steels are determined by the type of atomization used to manufacture each powder. A number of the general characteristics of PM stainless steels are described in the following sections.

Physical Characteristics of PM Stainless Steel Powders

The particle sizes of PM stainless steel powders can be determined by the water pressure applied during water atomization, where higher water pressures produce finer powders; for example, a pressure of 2000 psi (13.8 MPa) produces a powder with a particle size of ~100 mesh (150 μm) [41]. This pressurized water is usually directed into the liquid metal stream using V-jet nozzles, where the high pressure disintegrates the metal into fines. To produce a powder with a range of particle sizes, different water-jet configurations must therefore be employed. In general, the particles used in conventional PM have a particle size range of 25–300 μm, where the lower sizes correspond to a mesh count of ~500, which is too small to be measured using the mesh count technique, while the high end of this range corresponds to a mesh count of ~50. In addition, as a volume of loose powder contains pores between the particles, these open pores allow the free flow of fluids between the particles. This movement of fluid between the pores depends on both the size and the shape of particles, with larger particles allowing faster and easier movement of the fluid than smaller particles.

The shape of a PM stainless steel powder has a large influence on its green strength, flow characteristics, compressibility, and apparent density [42]. In addition, the shape of the powder also affects its sinterability, in addition to its behavior, including any dimensional changes during sintering, and its final mechanical properties. The particle shape is usually described in terms of the aspect ratio (i.e., the ratio of the maximum dimension to the minimum dimension for a given particle) and ranges from unity, for a spherical particle, to ~10, for a less regularly-shaped particle [14]. Furthermore, microscopic techniques are commonly employed to determine particle morphologies. More specifically, it has been found that of the various classification types of stainless steel powders, spherical particles result in higher flows compared to angular, spongy, rounded, flakey, or cubic particles, and their aspect ratio is also the lowest [14]. Indeed, in a single batch of powder, variation will exist both in the particle shapes and in the particle sizes.

Chemical Characteristics of PM Stainless Steel Powders

The major elemental components of stainless steel powders include iron, chromium, carbon, silicon, molybdenum, nickel, and manganese. The effects of chromium, nickel, and carbon were discussed in the previous sections and these will be elaborated on in the corrosion and properties sections. Like the physical properties, the chemical properties of stainless steel powders have a significant influence on the overall characteristics of the powders. For example, some constituents can affect the preferred oxidation states of Mn and Si during atomization and subsequent compaction. In addition to Cr and Ni, Si is also
considered a critical alloying element, as the majority of oxidation that takes place during water atomization involves the formation of silicon dioxide, due to silicon being one of the most commonly employed deoxidizing agents [42].

**POWDER COMPACTION, CONSOLIDATION, AND SHAPING**

**Powder Compaction**

Powder compaction comprises three main stages, namely the initial, middle, and final stages, which will now be discussed in detail. In the initial stage, densification is accomplished by re-arrangement of the powder particles to fill the large voids within the powder microstructure. In this stage, bridges between the powder particles are broken [43], and the applied pressure should be sufficient to overcome internal friction between the powder particles in the overall powder mass. Densification of the powder mass can be enhanced both by the smoothness of the particles and by the presence of lubricants. In the middle stage, the densification process is dominated by the elastic deformation of the powder particles. As the applied pressure increases, the interparticle contacts are plastically deformed, leading to the formation of, and interlocking between, protruding asperities on the surfaces of the powder particles [44]. In the final stage, plastic deformation of the particles becomes widespread and is accompanied by other processes such as cold welding (welding without the use of heat), shearing, and the formation of new oxide-free surfaces [45]. Shearing tends to take place due to the presence of asymmetrically opposed forces; therefore, irregularly-shaped particles experience a greater degree of shearing. The main changes in the powder morphology that occur during this stage of rigid die compaction is deformation of the powder particles and an accompanying reduction in porosity.

As the compaction process continues, the amount of pressure required to further densify the sample increases as plastic deformation leads to strain hardening of the powder particles. The green strength of the compacted mass is therefore a result of two main factors, i.e., the interlocking of rough particles with irregular surfaces, and cold welding at the particle surfaces as a result of shearing.

Figure 7 summarizes these major stages of powder densification during rigid compaction through a plot of green density as a function of compaction pressure. At low compaction pressures, the pores rearrange without deformation, leading to a rapid increase in density. In contrast, when the pores are more closely packed, plastic deformation takes place at the pore interfaces, leading to an increase in density, although at a significantly lower rate. At relatively high green densities, the powder behaves more like a solid.
Figure 7. Stages of densification of the powders during rigid compaction (Reproduced from ref. [40] with the permission of the Metal Powder Industries Federation).

The effect of applied pressure during compaction is also shown in Figure 8, which illustrates the microstructural changes taking place in the powder compact. As indicated, an increase in compaction pressure leads to an increase in the powder density after compaction, and the influence of pressure depends both upon the quantity and the packing density of the powder. More specifically, the depictions shown in Figure 8 indicate the different stages of powder compaction. Although the powder is initially loosely packed (i.e., high porosity), the subsequent application of a small amount of pressure results in rearrangement of the powder, which fills the voids and produces a denser powder, despite the contact stress between particles remaining low. Continued compaction results in an increased number of contact points between particles in addition to increased contact stress and plastic deformation of the powders, resulting in increased powder adhesion. As the pressure is increased further, the particles are plastically deformed, causing an increase in the interparticle contact area and additional contacts between particles, resulting in a further reduction in pore volume.

A graphical representation of green density as a function of applied pressure is a useful way of depicting the relationship between increasing compaction pressure and increasing powder green density for all metal powders, and not just for stainless steel alone. As shown in Figure 9(a), upon increasing the pressure, the compact density approaches that of the metal in its bulk form. The higher the density of the compacted samples, the higher its strength and elastic modulus (see Figure 9(b)), as a higher density essentially constitutes a greater quantity of solid metal in the same volume, thereby leading to an increased strength.
Compaction of Stainless Steel Powders

Several factors must be considered during the compaction of stainless steel powders, including the characteristics of the powder and the lubrication. For example, stainless steel powders that are to be formed using the PM technique must have sufficiently irregular particle shapes to exhibit a high green strength [45]. In addition, the powder must be able to densify and deform readily, so that the pressure applied during compaction is compatible with the available compacting tooling and presses. Furthermore, the powders should exhibit superior flow properties, i.e., they should fill a die cavity within a reasonably short period of time. Although stainless steel powders are normally compacted at slower rates than iron powders or low-alloy steels [14] due to the lower green strengths of the stainless steel powders, it has been reported that stainless steel powders with a green strength of ~15.2 MPa can be formulated at compacting pressures of 552 MPa while maintaining a good flow rate and compressibility [47]. Moreover, compared to low-alloy steel and iron powders, stainless steel powders exhibit a lower compressibility, and so require higher compaction pressures to reach the same green densities. It should also be noted that as stainless steel powders are abrasive to tooling parts, carbide tooling is essential.
Figure 9. The effect of compaction pressure on (a) the green density, and (b) the tensile strength, elongation, and electrical conductivity (Reproduced from ref. [46] with the permission of Pearson Education).
Lubrication must also be considered when compacting stainless steel powders, as it serves an important role in die compaction through assisting in the ejection of the green compact from the die, in addition to reducing die wear. Furthermore, it reduces friction between the particles, thereby reducing the pressure required to achieve the desired green density. A good lubricant will prolong the first step of rigid die compaction (i.e., the particle rearrangement stage) to yield a uniform density distribution [48]. However, the addition of lubricants can also have a negative effect on the green strength of the powder as it reduces the number of surface contacts between the powder particles. Generally, different lubricants have different effects on the green density, which is essentially determined by the amount of lubricant used, the particle size, the lubricant composition, and any lubricant-particle interactions. In general, the two most widely used lubricants for stainless steel powders are lithium stearate and ethylene bis-stearamide (EBS).

To date, several methods have been reported for the compaction and consolidation of PM stainless steel components, with the dominant processes including rigid die compaction, powder injection molding and hot isostatic pressing [14]. These processes will be described in more detail in the following sections.

**Rigid Die Compaction**

Rigid die compaction is the most widely used process for the consolidation of PM components as it is compatible with low-cost water-atomized powders [14]. It is also a versatile technique for preparing PM components with a wide range of geometries, and is reasonably cost-effective compared to other consolidation methods. The powder particles required for use in the die compaction process are irregular, which provides mechanical cohesion between adjacent particles. For large-scale production, powders with low cohesive forces require the use of a lubricant that can be added during blending in the form of micro-flake amides, waxes, soaps, or a mixture of these components. In the blending process, powders of the same chemical composition, but different particle sizes, are mixed.

Figure 10 shows a schematic representation of the active parts of a typical rigid die compaction tool. The lower punch is fixed to the press frame and constitutes the reference level of the tool. The cavity that holds the loose powder is formed by the lower punch, the core rod, and the die. This die is usually designed as a shrink-fitted single cylinder with a wear-resistant core in a medium strength steel shrink ring. In the compaction process, the upper press ram moves the upper punch downwards, resulting in a reduction in the length of the powder column by a factor of ~2–2.5. As shown in Figure 11, the production cycle consists of die filling, compaction, and ejection. Up to this point, the powder press has been equipped with a feed shoe to which the cavity is fully covered and gravity-filled with the free-flowing powder. To ensure that the compact is uniform, the feed shoe can be shaken several times. While approaching the cavity, the feed shoe pushes the ejected compact formed in the previous cycle over the die plate and out of the press.
Powder Injection Molding

Powder injection molding is suitable for manufacturing a large number of components with different geometries and is commonly applied in situations where dimensional tolerance, cost, and shape capabilities render it the preferred consolidation method [49]. It should be noted that the largest dimension that can be processed using powder injection molding is 100 mm [4, 40]. This technology evolved from the commonly known injection molding.
process for plastic components. Generally, compared to alternative fabrication methods, these components require precise and extensive drilling, machining, and/or grinding [50].

Previously, the most commonly used metal powders for powder injection molding included carbonyl-nickel and iron powders, in addition to fractions of fine atomized stainless steel powders obtained from coarse powders that are intended for other purposes [41]. Due to recent technological advancements (such as special gas-atomization techniques, high-pressure atomization, and hybrid gas-water atomization), a wider range of powder qualities can now be supported by powder injection molding at a greatly reduced cost [51]. The most common type of feedstock used in powder injection molding tends to be fine powders (i.e., <20 μm), near-spherical pre-alloyed metal powders, and elemental powders mixed with organic binders [52], which form a feedstock. As sintering is carried out rapidly to give significant shrinkage and densification, the employed particles must be particularly small [52]. In addition, a high packing density is achieved (i.e., resulting in a low porosity) by minimizing the amount of void-filling binders, thereby increasing the cohesive force among the particles [53].

The tools employed in powder injection molding are similar to those used in plastic injection molding. To ensure that the feedstock is efficiently utilized, runners and sprues are usually recycled [54]. In addition, the tools must be clean to increase the average tool life and reduce variations in the punch life.

Following injection molding, the subsequent debinding process removes the binding additives from the green compacts [55] to achieve effective sintering. For this purpose, a continuous catalytic debinding process is commonly employed, where the binder is combusted into the gas phase, yielding components with open porous structures, which can be referred to as the brown compact.

**Hot Isostatic Pressing**

Hot isostatic pressing (HIP) is a process that allows very high density (low porosity) components to be manufactured, thereby improving the mechanical properties and workability of the materials. Figure 12 shows a schematic representation of the typical HIP apparatus employed for this process. During HIP, materials are subjected to both high temperatures and high pressures in an inert atmosphere (usually Ar), in vessels equipped with sophisticated control systems and telemetry (i.e., equipment for taking measurements and carrying out data collection). In addition, the temperature is regulated to maintain plastic deformation of the material in the solid state, while the pressure is isostatically exerted on the heated segment for the desired time. The chamber is then slowly cooled, depressurized, and the components removed. Furthermore, the HIP process uses spherical gas-atomized powders with low oxygen contents [56], and is generally used in the production of simple components. Examples of the application of HIP-fabricated components exist in the defense (in ordinance), marine (components of marine diesel engines), architecture (in sputtering targets), oil/gas drilling (in valve components), and chemical industries (in pump bodies) [37].
Figure 12. Schematic representation of the HIP apparatus. Adapted from www.nhml.com.

Powders can also be compressed in a rolling mill operation to form metal strip stock, as depicted in Figure 13, where the process is usually set up to run continuously or semi-continuously. During this process, the powders are compacted between rolls to yield a green strip that is fed directly into a sintering furnace. This strip is then cold rolled and re-sintered. In such a powder rolling system, the metal powder is fed into the roll gap of a two high rolling mill (Figure 13), and is compacted into a continuous strip at speeds of up to 0.5 m/s. This rolling operation can either be carried out at room temperature (cold rolling) or at elevated temperatures. Sheet metal for electrical and electronic components is often produced using this process.

Figure 13. Schematic representation of a two high powder rolling system (Reproduced from ref. [26] with the permission of John Wiley and Sons).
SINTERING THEORY AND TECHNOLOGY

Sintering Mechanism

Sintering can involve either a single or a multi-component system. In a single component system, self-diffusion is the major driving force, and results from a chemical potential occurring due to capillary forces and surface tension between the powder particles [21]. In contrast, in multi-diffusion systems, inter-diffusion occurs where the concentration gradients are the major driving force. In this sintering method, the formation of both a solid solution and a liquid phase occurs with densification.

According to Sauerwald [21], who first proposed the sintering theory in 1922, sintering involves two stages, namely adhesion and recrystallization. According to this theory, adhesion is the result of atomic attraction during heating, while recrystallization occurs at the recrystallization temperature (considered to be >0.5T_m). During recrystallization, a number of changes occur, such as shrinkage and microstructural changes, which are due to grain growth and phase transformation.

During sintering, the loose metal powders or green compacts are consolidated into a component with the required composition over a controlled time and at a temperature lower than the melting point of the alloy. In modern sintering practices, the furnace atmosphere is controlled to protect the powder from oxidation and produce components exhibiting good mechanical properties, high corrosion resistance, and an adequate dimensional tolerance [57]. A reducing controlled atmosphere can also be employed to enhance the removal of existing oxides or provide a carburizing atmosphere to assist in the removal of any lubricants and binders employed during compaction.

As discussed previously, particle morphology has a significant effect on the sintering process, and in particular on the corrosion resistance of the system. As sintering consolidates the powder by promoting particle bonding, the intrinsic particle shapes and sizes are critical to this process. More specifically, sintering involves compacting followed by the subsequent formation of a solid mass of material by heat or pressure without melting it to the point of liquefaction. Upon increasing the bonding between particles, the empty pore space between the particles changes from a sharp and angular environment with a high surface area to a rounded environment with a low surface area. Following sintering, the increased density of the component results in an increase in both its strength and hardness. As shown in Figure 14, on the microscopic scale, particle bonding occurs at points of contact between the particles. Following removal of the binders, the powders are sintered, then cooled.

Sintering involves the mass transport of particles to create necks, which subsequently transform into grain boundaries. The principal mechanism by which this occurs is diffusion, although plastic flow can also occur. Shrinkage then occurs during sintering as a result of a reduction in the pore size, but this is largely dependent on the density of the green compact, which in turn depends on the pressure used during compaction. In general, shrinkage is predictable when the processing conditions are well controlled.
Figure 14. Schematic representation of the sintering process on a microscopic scale (Reproduced from ref. [26] with the permission of John Wiley and Sons). (1) Point bonding occurs at the contact points between particles; (2) contact points grow into necks; (3) pores between the particles reduce in size; and (4) grain boundaries develop between the particles at the neck regions.

Figure 15. Schematic representations of two different sintering mechanisms: (a) diffusion, and (b) vapor-phase material transport (Reproduced from ref. [46] with the permission of Pearson Education).

Figure 15 shows schematic representations of two different sintering processes on the microscopic scale, namely solid state transport (diffusion, Figure 15(a)) and vapor phase material transport (Figure 15(b)). The sintering mechanism taking place tends to depend on the composition of the metal particles and the processing parameters employed. In the solid state transport process, two adjacent powder particles begin to form a bond via mass diffusion as the temperature increases. As a result, the strength, density, ductility, and thermal and electrical conductivities of the compact increase. However, the compact shrinks due to the centers of the particles moving closer together; hence, allowances must be made for this shrinkage, such as those made in casting processes. In the vapor-phase transport mechanism, metal atoms are released into the vapor phase from the particles as the material is heated close to its melting temperature. At convergent geometries (i.e., at the interface of two particles),
the melting temperature is locally higher and the vapor phase re-solidifies. Thus, the interface grows and strengthens while each particle shrinks in size as the neck develops, thereby resulting in an increase in the distance between particle centers.

Types of Sintering

The main types of sintering processes employed to date include solid state sintering, liquid phase sintering, reaction sintering, and activated sintering. Solid state sintering is the most common sintering process for the consolidation of PM components, where densification occurs mainly as a result of atomic diffusion in the solid state [14]. The main stages involved in this process (see Figure 14 above) are as follows:

**Stage one:** Necks are formed at points of contacts between the powder particles, and these necks continue to grow with increasing temperature/time. During the rapid formation of these necks, the pores between the powder particles become interconnected.

**Stage two:** Following neck growth, the channels formed from interconnections of the pores become increasingly cylindrical. It is important to note that when the neck size is insufficient, the rate of sintering is extremely high due to a high surface area [14]. Given sufficient time at the desired sintering temperature, the pores between the particles eventually equilibrate to become spherical. As the necks grow, both the gradient of the curvature and the resulting sintering rate decrease.

**Stage three:** The channels of the pores begin to close and become completely isolated from other pores. This is the final stage of solid-state sintering and the porosity of the sintered component remains constant.

During liquid phase sintering, densification is enhanced by the presence of a liquid phase constituting ~1–10% of the total sample volume. Generally, this liquid phase is formed at the interface between the powder particles and enhances the solubility of the solid under the sintering conditions. During sintering, the liquid phase crystallizes at the grain boundaries and binds the particles together [14]. In addition, the solid particles rapidly rearrange to increase the density. However, if liquid phase sintering is prolonged, it can cause grain coarsening and a reduction in the densification rate.

In the activated sintering process, the sintering rate is increased by optimizing the sintering conditions or by the addition of certain substances, such as sintering aids. In this type of sintering, doping with a small amount of an alloying element [14] is carried out to enhance the densification process.

Sintering of Stainless Steel

The sintering process is of great importance during the processing of successful PM stainless steel components and can be influenced by a number of factors, namely the type of sintering furnace, the sintering temperature, the sintering atmosphere, and the choice of processing parameters. Indeed, all of the above factors can affect the quality of the sintered components, as discussed below.

Commercial sintering is commonly carried out in continuous mesh belt conveyor furnaces at high temperatures (~1150 °C) [58]. In addition, vacuum furnaces, walking beams,
pushers, walking beam furnaces, and ceramic-belt furnaces are used for sintering at higher temperatures ($\leq 1345^\circ C$) [14]. In such cases, the use of high temperature sintering results in improved corrosion resistances and enhanced mechanical properties. Figure 16 shows a schematic representation of a microwave sintering furnace. Although metals tend to reflect microwaves when in their solid, nonporous form, metals in the form of a powder will absorb microwaves at room temperature, thereby resulting in effective and rapid heating [6]. This technology can therefore be employed to sinter various powder metal components, and has produced a number of useful products to date, including small cylinders, rods, gears, and automotive components. Microwave heating and sintering are fundamentally different from conventional sintering, which involves radiant/resistance heating followed by the transfer of thermal energy via conduction to the inside of the body being processed. Instead, microwave heating is a volumetric heating method involving the conversion of electromagnetic energy into thermal energy, which is instantaneous, rapid, and highly efficient. As such, this process tends to result in the formation of fine microstructures, thereby yielding improved mechanical properties and better product performances.

Typical atmospheres for sintering stainless steel include dissociated ammonia (DA), vacuum, hydrogen, and hydrogen-nitrogen mixtures. Hydrogen and hydrogen-nitrogen mixture environments have the capability of reaching low dew points (the temperature at which the water vapor present in the sintering system will saturate the sintering atmosphere [59]; this is used to estimate the quantity of water vapor present in the sintering system), which is of particular importance for sintering, as when cryogenic nitrogen is used in hydrogen-nitrogen mixtures, it is easier to achieve low dew points. However, as hydrogen-nitrogen mixtures are also reducing agents, they require lower dew points compared to pure hydrogen atmospheres. Thus, since low cost sintering atmospheres are preferred, stainless steel components are occasionally sintered in hydrogen-nitrogen atmospheres containing as little as 3% hydrogen [14], thereby producing components exhibiting extremely low corrosion resistance properties (see the following subsection for further details). It should also be noted that as Cr loss can occur when sintering in a vacuum due to the high vapor pressure, vacuum sintering is normally carried out at low pressures of ~1–3 mm Hg (i.e., 0.13–0.4 kPa) [14].

![Figure 16. Schematic representation of a microwave sintering furnace. Adapted from www.azom.com.](image-url)
Optimized Sintering

To ensure that the desired properties of the sintered component are achieved, it is important that the sintering process is carried out under optimal conditions, as indicated below:

1. To avoid excessive oxidation during sintering under a hydrogen atmosphere, sintering must be carried out at a reduced dew point [14], otherwise extensive deterioration of the mechanical and corrosion-resistance properties can take place.
2. To achieve low-carbon stainless steel, the carbon content must be maintained at low levels to prevent chromium carbide precipitation. For example, for slowly cooled austenitic stainless steels, the carbon content must be in the range of 0.02–0.03%.
3. For high-carbon stainless steel, the rate of cooling must be sufficiently high to prevent/minimize chromium carbide precipitation.
4. For stainless steels with carbon contents >0.03% prepared using a slow rate of cooling, niobium must be added to stabilize the product and prevent sensitization.
5. To avoid re-oxidation and pitting following sintering, cooling must be sufficiently fast (i.e., ≤400 °C/s).
6. Contamination with corrosion-causing elements (such as nitrogen and oxides) must be prevented unless these contaminants are dissolved and homogenized during the sintering process.
7. To avoid Cr₂N formation (which can result in intergranular corrosion) during sintering in nitrogen-containing atmospheres, the cooling rate should be sufficiently high. For example, for sintering carried out in DA, the rate should range from 200 °C/min to >450 °C/min, depending on the dew point.
8. Sintering in a vacuum must be carried out under conditions that do not permit the depletion of surface chromium through vaporization (e.g., at increased partial pressures to replenish any surface chromium that was lost during low partial pressure sintering).

THERMAL AND COLD SPRAYING

During operation, structural components are normally subjected to harsh conditions, thereby resulting in a reduction in their service lives [60]. Thus, to protect components against corrosion and wear, surface coating methods using PM routes have been developed. One of the main types of coating, developed in the early 1900s, is thermal spraying, in which a melted (or heated) material (such as stainless steel powder) is sprayed onto a metal surface [61]. With the development of the plasma spray gun in the 1960s, high-temperature coating using stainless steel became commercially viable. This plasma spraying process employs a direct current electric arc to generate a high-temperature stream of ionized gas (plasma), which serves as the spraying heat source [18]. Successful coating using stainless steel is typically carried out in a plasma stream of an inert gas, as the temperature of the plasma jet is extremely high (i.e., ~15000 °C) [62].
Further advances in the plasma spraying principle led to the development of other spraying methods, such as flame spraying, warm spraying, cold spraying, wire arc spraying, high velocity spraying, and detonation spraying [63]. These methods introduced the use of a multitude of different spraying materials for diverse and demanding applications, such as aerospace applications. In general, these coatings provide resistance to wear, erosion, cavitation, corrosion, abrasion, and heat [64].

In cold spraying, powder particles measuring 10–50 µm are sprayed by a compressed gas jet at high velocities (200–1000 m/s) and at temperatures typically lower than their melting point [65]. Upon striking the substrate, the powder particles undergo plastic deformation. This results in removal of the thin metal oxide layer from the surface of the deformed metal powder [24, 66], enabling intimate contact with the exposed surfaces of other particles under a high local pressure. This in turn results in metallurgical bonding and the rapid formation of a thick film layer [11, 67]. Figure 17 shows the scanning electron microscopy microstructure of an etched 316L stainless steel coating deposited by cold spraying. In addition, novel cold spraying methods have also been developed to expand the potential applications of this technique, including cold spraying that incorporates shockwaves produced by pulsing high pressure gas at frequencies of 10–30 Hz by quickly opening and closing valves. The resulting generated pulse then accelerates heating of the stainless steel powder. This new technique has been effectively demonstrated for processing the powders of stainless steel, titanium, and cermets, among other materials [65].

Figure 17. Microstructure of a 316L stainless steel coating deposited by cold spraying [68].

**MECHANICAL TESTING AND PROPERTIES**

**Factors Affecting the Mechanical Properties of PM Stainless Steel**

Various factors are known to affect the mechanical properties of PM stainless steel, including the interstitial content and sintering atmosphere, the sintering temperature and time,
the porosity, the thermal history, and the cold working history. These factors will now be discussed in more detail.

Stainless steel and other PM materials are exposed to a wide variety of interstitial contaminants, such as carbon, nitrogen, and oxygen, during sintering [69]. The inclusion of such interstitial elements depends on the sintering parameters employed during the process, including the cooling rate, sintering time, sintering temperature, type of lubricant, sintering environment, dew point, alloy composition, and the efficiency of lubricant removal [70].

The wide range of oxygen contents found in the starting stainless steel powders may also affect the quality of the sintered products. For example, if the quantity of residual oxygen is high after sintering, the mechanical strength and ductility of the sintered product will be adversely affected. According to the literature, the tensile strength of sintered PM components increases significantly if the quantity of oxides is reduced [71], while the yield strength appears unaffected [72].

The effect of the sintering temperature on the mechanical properties of PM stainless steel products is significantly higher than that of the sintering time [72]. At low sintering temperatures, the rates of inter-particle bonding, pore spheroidalization, and surface oxide reduction are low [73]. This results in a reduction in the tensile strength, ductility, and impact strength of the final component [74].

In the conventional processing of low-alloy PM stainless steel, porosity also plays an important role in determining the mechanical strength of PM stainless steel components when compared to wrought stainless steel components. However, the effect of porosity in PM stainless steel can be overshadowed by the effect of interstitial elements. Typically, stainless steel normally exhibits a density in the range of 6.6–7.3 g/cm$^3$ (c.f., the bulk density of stainless steel, 7.95 g/cm$^3$) [32]. When the effect of porosity is taken into consideration, it has a pronounced impact on the static mechanical properties, such as strength and fatigue [7, 17]. Such negative effects are normally greater for brittle components than for ductile materials.

The thermal and cold working histories of the material can also affect the mechanical properties of PM stainless steel, as mentioned previously. For ease of understanding and discussion, the mechanical properties of stainless steel can be divided into two main categories, i.e., room temperature and high temperature. These two categories will be discussed in further detail in the following subsections.

Mechanical Properties (As-Sintered Condition)

PM components are often designed to meet a given structural criteria specific to their intended application. Typically, mechanical or sintered structural components can be produced that exhibit properties similar or comparable to those produced using more traditional routes. Tables 1 and 2 summarize the mechanical properties of various PM stainless steel and PM ferritic stainless steel samples and compares the effects of both composition and sintering conditions.

Several factors are known to influence the fatigue behavior of PM stainless steel, where the density of the sintered product is dominant [67], as sintered components with fine rounded pores exhibit superior dynamic mechanical behaviors than those with coarse angular pores [22, 75]. According to the literature, porosity plays a particularly important role in the
Table 1. Mechanical properties of PM stainless steel (as-sintered condition) [14]

<table>
<thead>
<tr>
<th>Base alloy</th>
<th>% C</th>
<th>Sintering temp (°C)</th>
<th>Sintered density (g/cm³)</th>
<th>Sintering atoms</th>
<th>% N₂</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Elongation (%)</th>
<th>Hardness (HRC)</th>
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<td>90 H₂/10 N₂</td>
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Table 2. Mechanical properties of PM ferritic stainless steel [14]

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<th>Yield strength (MPa)</th>
<th>Elongation (%)</th>
<th>Hardness (HRC)</th>
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Table 3. Mechanical properties of PM austenitic stainless steel [14]

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<th>Elongation (%)</th>
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</table>

DA = dissociated ammonia; Atmos. = atmosphere.
initiation and propagation of fatigue cracks [76]. The presence of such cracks initiates rapid initial strain hardening, and the plastic zones surrounding the pores strain harden at relatively low strain levels [77]. This leads to the gradual growth of plastic zones. In contrast, pore-free materials undergo more homogeneous strain hardening. When a crack develops close to a pore, it grows rapidly in the pore-induced plastic zone [41]. When this crack reaches a lower strain region, the growth rate slows. Hence, work hardening is an important aspect when determining crack initiation [75]. For example, since austenitic stainless steel work hardens at a higher strain rate than ferritic stainless steel, its undergoes more rapid fatigue crack initiation [78].

Porosity also plays an important role in reduction of the crack growth rate. When the crack reaches the pore, the stress that is concentrated at the tip of crack is released and a new blunt crack is formed on the opposite side of the pore [79]. Crack growth may therefore stop if the concentration of stress on the opposite of the pore is insufficient. Other factors that may affect the fatigue behavior of PM stainless steel are the microstructure, the pore structure, and the presence of non-metallic inclusions, nitrides, and carbides.

**Mechanical Properties at Elevated Temperatures**

Sintered PM stainless steel tends to exhibit lower tensile and yield strengths than wrought stainless steel due to its larger grain size. At temperatures higher than the recrystallization temperature (i.e., when the grains begin to enlarge), deformation occurs owing to grain boundary sliding, and therefore, coarse grain structures tend to exhibit reduced yield strengths at elevated temperatures. In addition, PM stainless steels sintered at high temperatures tend to exhibit clean grain boundaries with respect to constituents such as carbon, phosphorus, and nitrogen [79].

**Creep and Stress Rupture Properties**

Creep is typically defined as the time-dependent deformation of a material under an applied load below its yield strength. Creep occurs mainly in applications of heat resistant high alloy castings and has the ability to cause excessive deformation and fractures. These failures can occur at stresses below the critical values determined at room temperature. Stress rupture testing is therefore designed to determine the time required for component failure to occur. Typically, the stress value designed into a component is based primarily on the minimum rate of creep and the required lifetime, after considering the initial transient creep. This initial transient creep takes place when the degree or rate of deformation is the limiting factor [14]. Table 3 shows the stress and rupture lifetimes of stainless steel under different conditions [14].
Table 3. Stress and rupture lifetimes of stainless steel samples tested under different testing temperatures and stress conditions [14]

<table>
<thead>
<tr>
<th>Material and density</th>
<th>Test temperature</th>
<th>Stress</th>
<th>Rupture life</th>
<th>Steady-state creep rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(°C)</td>
<td>(°F)</td>
<td>(MPa)</td>
<td>(ksi)</td>
</tr>
<tr>
<td>PM 409LE 7.35 g/cm³</td>
<td>649</td>
<td>1200</td>
<td>69.0</td>
<td>10.0</td>
</tr>
<tr>
<td>PM 409LE 7.35 g/cm³</td>
<td>649</td>
<td>1200</td>
<td>86.2</td>
<td>12.5</td>
</tr>
<tr>
<td>PM 409LE 7.35 g/cm³</td>
<td>649</td>
<td>1200</td>
<td>103.4</td>
<td>15.0</td>
</tr>
<tr>
<td>PM 409LE 7.35 g/cm³</td>
<td>649</td>
<td>1200</td>
<td>103.4</td>
<td>15.0</td>
</tr>
<tr>
<td>PM 409L 7.30 g/cm³</td>
<td>677</td>
<td>1250</td>
<td>57</td>
<td>8.3</td>
</tr>
<tr>
<td>Wrought 409L</td>
<td>677</td>
<td>1250</td>
<td>30</td>
<td>4.4</td>
</tr>
<tr>
<td>PM 409L 7.15 g/cm³</td>
<td>677</td>
<td>1250</td>
<td>68</td>
<td>9.9</td>
</tr>
<tr>
<td>PM 409L 7.15 g/cm³</td>
<td>677</td>
<td>1250</td>
<td>60</td>
<td>8.7</td>
</tr>
<tr>
<td>PM 409L 7.15 g/cm³</td>
<td>677</td>
<td>1250</td>
<td>55</td>
<td>8.0</td>
</tr>
<tr>
<td>Wrought 409L</td>
<td>704</td>
<td>1300</td>
<td>28</td>
<td>4.1</td>
</tr>
<tr>
<td>Wrought 409L</td>
<td>704</td>
<td>1300</td>
<td>22</td>
<td>3.2</td>
</tr>
<tr>
<td>Wrought 430L</td>
<td>649</td>
<td>1200</td>
<td>30</td>
<td>4.4</td>
</tr>
</tbody>
</table>

**CORROSION TESTING AND PERFORMANCE**

Sintered components must be tested for corrosion resistance for a number of reasons, such as those outlined below:

1. To check whether the produced material meets the required standards of corrosion resistance for its intended use [80];
2. To develop corrosion resistance standards [81];
3. As an assurance to a customer that the material meets the accepted criteria [42, 82];
4. To develop superior quality materials;
5. To monitor specific aspects of processing;
6. To troubleshoot corrosion-related failures; and
7. As general quality control during stainless steel manufacture [21].

In terms of the different types of corrosion, intergranular corrosion refers to the corrosion between grains. More specifically, it is a form of corrosion where the crystallite boundaries of the material are more susceptible to corrosion than the bulk. The microstructure of a stainless steel sample can therefore show either a normal or a sensitized microstructure, as indicated in Figures 18(a) and 18(b), respectively, where the normal microstructure exhibits no corrosion, but the sensitized microstructure is corroded.

In general, the mechanism and extent of corrosion depend on the degree of sintering, with the level of corrosion being affected by the sintering conditions employed, such as different temperature and time regimes. Figure 19 shows the cross-sectional images of two different levels of sintering, i.e., an under-sintered cross-section that is characterized by prior particle boundaries and angular pores (Figure 19(a)), and a sintered cross-section that is characterized by inter-particle bonding, twin boundaries, twin pores, and precipitate-free grain boundaries (Figure 19(b)).
Figure 18. Microstructures of stainless steels samples that are (a) not susceptible to corrosion, and (b) susceptible to corrosion (i.e., showing intergranular corrosion). Taken from http://en.wikipedia.org/wiki/Intergranular_corrosion.

Figure 19. Cross-sectional micrographs of (a) under-sintered, and (b) well-sintered stainless steel samples (Reproduced from ref. [14] with the permission of ASM International).

**Corrosion Tests**

Various types of tests are used to evaluate the corrosion behavior of PM stainless steel components, including, immersion, salt spray, electrochemical, ferric chloride and ferroxyl, and elevated temperature oxidation (corrosion) resistance tests. These test methods will now be discussed in further detail.

**Salt Spray Test**

In recent years, the salt spray test has been employed as a quality control test for PM stainless steel components aimed at substituting wrought stainless steel components [83]. As PM stainless steel components are normally subjected to atmospheric conditions during their application, it is important that they undergo long-term salt spray testing, which is considered to be a realistic test for the environmental conditions that such a component may be subjected to during its service life. This test is sensitive to porosity and other metallurgical defects [84], and can also be used during optimization of the sintering process. Compared to natural salt
immersion, the natural salt spray test is more aggressive and a so visual rating can be applied [85].

**Immersion Test**

The aim of laboratory corrosion testing is to simulate environmental conditions and accelerate corrosion over a reasonable time period. In an immersion test, accelerated corrosion is achieved by lengthening the exposure to critical conditions that are suspected to result in corrosion damage. This can also be achieved by intensifying the conditions to increase the corrosion rate. In this context, the immersion test involves the immersion of samples in natural salt solutions and acids, and is the most widely used corrosion test for sintered stainless steel components due to its inherent simplicity [17]. Although this corrosion test is sensitive to the various different forms of corrosion, it does not provide information regarding the corrosion mechanism from a rust development and/or simple weight loss standpoint [86]. However, when the test is combined with chemical and/or metallographic analyses, information regarding the corrosion mechanism can be determined [87,88].

In addition, immersion tests in acids usually result in sample weight loss, which can subsequently be employed to calculate the corrosion rate [58] as shown below [89]:

\[
\text{Penetration rate} = 87.6 \frac{W}{DAT}\text{ (mm/year)}
\]

where \(D\) is the density of the specimen (g/cm\(^3\)), \(W\) is the weight loss (mg), \(A\) is the specimen surface area (cm\(^2\)), and \(T\) is the exposure time (h).

Corrosion rates are usually classified as shown in Table 4, where the recommended minimum test period is ~90 d when employing metal coupons in a corrosion test rack. The water flow should be continuous over the test period to ensure that a meaningful corrosion rate is measured.

<table>
<thead>
<tr>
<th>Corrosion rate (mm/y)</th>
<th>Classification/Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.02</td>
<td>Outstanding</td>
</tr>
<tr>
<td>0.1–0.5</td>
<td>Good</td>
</tr>
<tr>
<td>0.5–1</td>
<td>Fair</td>
</tr>
<tr>
<td>1–5</td>
<td>Poor</td>
</tr>
</tbody>
</table>

**Electrochemical Corrosion Tests**

The electrochemical cell used for electrochemical corrosion tests consists of an electrolyte solution, a counter electrode, a reference electrode, and the sample of interest (acting as the working electrode), which is connected to a sample holder. The electrodes are then connected to a potentiostat. The chemical constituents required to prepare the corrosion environment are placed into the electrolyte solution and a voltage is generated between the electrodes. The potentiostat is then employed to measure the corrosion potential as an energy difference between the working and reference electrodes. These electrochemical corrosion tests provide both qualitative data for comparing different samples and, more importantly, quantitative corrosion rates. This test can also give information regarding the corrosion
mechanism [90] in addition to details regarding the effect of alloying elements on the behavior of stainless steel in terms of anodic polarization [87]. Although the criteria for the characterization of sintered materials can be applied for wrought materials, the presence of metallurgical defects (including porosity) can make interpretation of the electrochemical data complicated [91]. Significant care must therefore be taken to minimize the effects of sample preparation (e.g. cleaning, degreasing, and polishing of the sintered components).

**Ferric Chloride and Ferroxyl Tests**

The ferric chloride test employs a ferric chloride solution to test wrought stainless steel and sintered PM stainless steel samples for crevice erosion and pitting [92]. For the ferroxyl corrosion test, a hexacyanoferrate (II/III) solution is typically employed in addition to a variable quantity of sodium chloride (NaCl). This type of test can identify metallurgical defects resulting from iron contamination or improper sintering conditions [92].

**Elevated Temperature Oxidation Tests**

Due to the current use of sintered stainless steel in applications such as automotive exhaust systems, which subject components to elevated-temperature oxidation, it is important that all components exhibit good oxidation resistance. The presence of pores in the sintered components can decrease oxidation resistance [93], as porous materials exhibit different oxidation kinetics to bulk metals, with high porosity leading to increased oxidation upon increasing the temperature. However, attempts have been made to improve the oxidation resistances of PM components based on the principles of oxidation that were developed for solid metals [94].

A large number of alloys that exhibit low corrosion tendencies at high temperatures rely on the presence of Cr to form an oxide scale to protect against oxidation [3]. Other metallic elements, such as Ni, are also capable of forming a protective layer and normally exhibit parabolic oxidation behavior over time [95]. This occurs because these alloys rely on the presence of such protective elements to form a protective oxide scale throughout the oxidation process, as previously described for Cr. Hence, the migration of electrons or ions via the oxide layer controls the rate at which oxidation occurs. According to the Wagner theory of oxidation, ‘the concentration of ionic defects, and therefore the rate of oxidation, can be influenced by doping and by changing the phase structure through alloying’ [14].

**Effect of Sintering on Corrosion Resistance**

The main purposes of sintering during stainless steel processing are to form an integral piece through particle coalescence and to promote corrosion resistance [88]. If sintering is carried out in an appropriate environment and the desired corrosion resistance is achieved, the obtained components tend to exhibit superior mechanical properties to those sintered in a non-protective atmosphere [67].
APPLICATIONS OF POWDER METALLURGY PRODUCTS

Structural Applications

Powder metallurgy products have found wide applications in the automotive industry, including in exhaust systems, parts of antilock braking systems, and rearview mirror brackets. More specifically, automotive exhaust systems are one of the major applications of PM products. Due to strict environmental regulations and consumer demand for long-lasting components, PM stainless steels are used for the preparation of various components, as detailed in Figure 20 [96]. These components include sensor bosses and hot exhaust gas outlet fittings and flanges. According to the requirements of this application, these components must perform well at both ambient temperature and at elevated temperatures, in addition to resisting environmental corrosion, being weldable, resisting oxidation, and exhibiting good gas-sealing properties [97]. As PM components exhibit these characteristics, they are considered suitable for use in automotive exhaust systems. In addition, the good surface finish, desired flatness, and dimensional accuracy provided by PM components allow a good gas-sealing quality to be achieved [98, 99].

Furthermore, the sensor rings present in antilock braking systems must exhibit good ductility, mechanical strength, and precise dimensions. These rings should also demonstrate appropriate magnetic properties, and their resistance to environmental corrosion must be sufficient to survive exposure to harsh road conditions [100, 101]. To achieve these desired properties, a number of PM stainless steels have been developed, with the majority of antilock braking system sensor rings being composed of 434L, 410L, and modified 434L stainless steel grades, as shown in Figure 21 [101]. Moreover, to ensure good magnetic properties (maximum induction, low remittance, low coercive force, and high permeability [102]), the nitrogen content should be <50 ppm. Sintering at high temperatures and the introduction of low levels of interstitial elements may also enhance both the magnetic response and the corrosion resistance of the material [103].

Figure 20. Schematic representation of an exhaust system fabricated from parts composed of different PM alloys (Reproduced from ref. [14] with the permission of ASM International).
The brackets of car rearview mirrors are mainly composed of 434L, 410L, and 430L stainless steels prepared through sintering in hydrogen or DA between 1121 and 1149 °C. These bracket materials tend to exhibit a sintered density of ~7.1 g/cm³ [92, 104]. However, for such applications, the requirements regarding mechanical properties and corrosion resistance are not particularly demanding. Nevertheless, the coefficient of thermal expansion of the bracket must be close to that of glass [27], as these metal brackets are normally attached to the car windshield. Figure 21b shows a photographic image of a stainless steel bracket for an automotive rearview mirror.

In addition to the automotive industry, PM technology has made a major contribution to power generation [14]. Components of power plants, such as turbines, are normally subjected to extreme conditions of corrosion, oxidation, wear, and elevated temperatures. These components must therefore be able to survive such extreme conditions in addition to being strong enough to withstand the applied torque.

### Electrical and Magnetic Materials

Both hard and soft magnetic materials can be produced using PM techniques, which is advantageous in terms of the benefits associated with near-net shaping and control of the chemistry. The most suitable methods for the low-cost production of a large quantity of near-net shaped magnetic components are conventional compaction, sintering methods, and powder injection molding, where the latter can produce components that are nearly fully dense.

The major applications of PM soft magnetic materials, such as ferritic stainless steel, include the telecommunication industry, computers, automotive applications, office equipment, and household appliances [14]. Such applications often involve the conversion of electrical energy into mechanical energy, and so the material must be able to respond to low remanence and should also respond rapidly to any applied field. In addition, these materials must exhibit a low coercive field (i.e., the measure of a material to withstand an external field, high induction, or high magnetic permeability). Furthermore, the use of such materials in antilock brake sensor systems involves the conversion of motion into an electrical signal, and so a moderate coercive field and induction is essential.
Biomedical Applications

The introduction of stainless steel for biomedical implants had a particularly large impact on the biomaterials industry due to its excellent corrosion resistance [51]. Of course, the type of biomaterials used in an implant depends on the specific application. For example, 316L type stainless steel is the most widely used alloy in surgical implants, with common applications ranging from cardiovascular to orthodontic purposes [51, 57]. Figure 22 shows a photographic image of a PM stainless steel component for a surgical robot.

![Photographic image of a PM stainless steel component for a surgical robot.](image)

Figure 22. Photographic image of a component for a surgical robot created using high-resolution metal laser sintering of PM stainless steel. Adapted from www.micromanufacturing.com/content/sintering-3d-parts-powdered-metal-rise.

Other applications

In addition to the applications discussed above, PM stainless steels are also employed in a range of other applications, such as flame arrestors, filters, distribution and metering of gases and liquids, hearing aids, and parts for welding. In addition, sintered stainless steel is commonly used for household applications where hygiene standards are of great importance [14].

TECHNO-ECONOMIC ASPECTS OF POWDER METALLURY PROCESSING

Evaluation of the use of PM in the production of structural components is based on the comparison of its cost with that of other methods employed to produce the same component, the final product characteristics, the raw material utilization efficiency, and the degree of energy consumption (generally, lower energy consumption is preferred) [10]. In addition, the economic and technical qualification of PM as a method for component processing depends on a number of factors. For example, the geometry of the product is of particular importance. In this context, PM is suitable for forming prismatic products with limited complexity in a single dimension (i.e., through the axial/thickness dimension), but with unlimited complexity in the other two dimensions (i.e., the plan- or radial-view) [10].

In addition, the weight and size of the product is important. Upon comparing billet or steel bars that are prepared using either PM or conventional processes, the powder feedstocks required for the PM process tend to be expensive, even considering the efficient material utilization of PM. Therefore, PM is suitable only for the production of relatively light and
small components where the associated material costs can be limited to a small percentage of the total cost of manufacturing (i.e., ~20%) [10]. Furthermore, as the compaction pressure of current PM compaction processes is limited to a maximum of 1,000 tons, this procedure is not suitable for the preparation of parts bearing a large plan-view geometry. Moreover, components with larger plan-view geometries require larger compaction pressures.

Finally, in the context of product quantity, production runs must be large enough for PM to become economically viable. However, the tooling process is expensive and complex, and the capital cost associated with the PM equipment is high. These costs should therefore be amortized through the production of a large quantity of products [10].

**CONCLUSIONS**

In conclusion, the use of powder metallurgy (PM) technology is important in the manufacture of various metal alloy components for a range of applications, and so its use has grown significantly in recent years. To optimize the efficiency, component quality, and process time/cost of PM, modern techniques have largely replaced traditional methods, thereby resulting in significant reductions in factors such as sintering temperatures and times. Currently, stainless steel components can be produced in commercial quantities with competitive costs and manufacturing times, which has been made possible through immense efforts to improve PM stainless steel processing techniques, properties, and applications. This improved understanding of the processing parameters and their optimization is essential to produce components with appropriate properties and extend the use of the economically valuable PM technology to an increasing number of applications.

**REFERENCES**


Powder Metallurgy of Stainless Steel…


Powder Metallurgy of Stainless Steel


