2012

PM INDUSTRY ROADMAP

Technology Update
for the Powder Metallurgy Industry

METAL POWDER INDUSTRIES FEDERATION

EXECUTIVE SUMMARY

Powder Metallurgy (PM) has firmly established itself as a leading material and processing system for producing high-quality components for a wide variety of important applications. Historical annual growth rates of as high as 11 percent were a testament to the importance of the PM industry to the North American industrial community. In order to sustain that importance, in 2001 the PM industry, under the auspices of the Metal Powder Industries Federation and invited end users, academia and consultants, published the ***PM Industry Vision and Technology Roadmap****.* The two-year effort drew on the expertise, knowledge, and experience of a broad-based group of over 65 industry executives.

The PM industry has made significant progress in the technology challenges identified in the original Roadmap. High-density processing is commonplace today through the use of improved tooling materials enabling higher-tonnage compaction, warm compaction, and die-wall lubrication. Material advances in improved lubricants, lower-cost alloys and sinter-hardening powders have increased densities and broadened applications. Work continues on improving 3-D forming systems and making them more available. Technical advances in modeling, sensors, and controls continue to take place. Advanced manufacturing techniques and methods related to quality, productivity, and time compression are in wide use today.

Now, 10 years after its publication, the PM industry has come together once again to assess and update the Technology Roadmap. While the Vision remains the same—to be the preferred source of net-shaped, metal-based systems—much progress has been made and many changes have taken place in the technology landscape. Over the course of numerous sessions, dozens of industry representatives have re-identified the technical barriers, challenges, opportunities, and priorities that will drive the PM industry's continued growth in the future. The main topics identified are:

- High-density PM components
- Processing of lightweight materials
- Electrical and electromagnetic applications

This 2011 update document is not meant to replace the original 2001 Technology Roadmap; that document is still valid and relevant and should continue to serve as a reference for the PM industry's vision and future direction. However, this 2011 update incorporates the new market drivers and technical challenges that will help redefine our technology and impact the industry's future growth. All references are as of 2011 unless otherwise noted.

KEY MARKETS AND DRIVERS

The current PM industry is driven by applications in the automotive market. Future growth markets for PM technology over the next 10 years include electrical and electromagnetics, alternative energy, aerospace, medical, defense, industrial and consumer products.

Environmental concerns will significantly alter the focus of the automotive sector, the industry's largest customer. Higher fuel efficiency through improvements in engine performance, weight reduction, and alternative or supplemental power systems will be key drivers.

The need for alternative energy sources will drive new markets and applications for PM.

The aging population will continue to create PM applications in the medical industry.

Global economic development and rising living standards will have a significant impact on PM in consumer products.

MARKETS AND CUSTOMER DEMANDS

The industry must respond to the changing needs and demands of existing and potential customers with agility and ingenuity while maintaining higher value than competing materials technologies.

Automotive

Innovative design takes into account both the strategic advantages of sustainability and minimizing adverse environmental impact. PM's sustainable value is primarily derived from its net-shape capabilities and its high material-utilization that minimizes energy inputs, reducing the impact on the environment.

Legislation to improve fuel efficiency is a driving force. The 2016 Corporate Average Fuel Economy (CAFE) goal of 35.5 mpg will increase to 54.4 mpg in 2025 resulting in a decreased dependence on the internal combustion engine, a fact that will challenge the ferrous PM industry. Fuel efficiency continues to be increased with the help of PM in variable valve timing (VVT), continuously variable transmissions (CVT), direct injection, electric power steering, turbochargers, among other systems. The uses of biofuel and ethanol, however, have challenged the integrity of some existing materials providing an opportunity for new PM alloys development.

Opportunities will arise for the PM industry to supply hybrid-electric vehicle components including insulated gate bipolar transistors (IGBT), fuel cells, electric motors, and gears. For example, the market potential for automotive transmission gears is a strong motivator for the PM industry. The gear market is believed to be nearly the size of the entire PM market. Fully dense PM gears, with mechanical properties and surface finishes comparable with cut gears, would ultimately be preferred by automotive designers.

Electrical and Electromagnetic

The continued development of insulated powders for hard and soft magnetic applications is fundamentally changing the opportunities for the design of motors. Designers are not constrained to use stacks of laminations to build motors. The multitude of shapes that can be pressed or molded into stators and armatures using PM consolidation techniques and powders without a loss in electrical performance characteristics will revolutionize this sector. Advanced consolidation capabilities will enable production of motors using new materials. With the advent of hybrid propulsion systems for transportation, the design and weight advantages of PM will create market opportunities for the technology.

Alternative Energy

The reduction of greenhouse-gas emissions and the realization that fossil-fuel reserves are finite will continue to be a global focus. Governments and communities must confront the critical problem of domestic energy issues. For example, the European Union's target is to reduce greenhouse-gas emissions by 20% in 2020, compared with 1990 levels. This could result in a 30% increase in new alternative-energy sources.

Industries involved in alternative energy are an opportunity for the PM industry. Wind energy, solar energy, fuel cells, and energy-storage industries require bearings, gears, adaptors, clamps, electric motors, generators, sensors, switches, interconnects, coatings and powders—all prospects for PM.

Aerospace

The aerospace industry is expected to grow at a rate of 5% per year for the next 20 years, driven primarily by growth in Asia. Like automobiles, aircraft will be forced to become more fuel efficient due to higher fuel costs and pressure to reduce greenhouse-gas emissions. Airframes will become lighter through the use of composites, titanium, and new aluminum and magnesium alloys, but this domain offers limited opportunities for traditional PM. However, titanium PM HIP (hot isostatic pressing) and titanium additive manufacturing technologies should find opportunities in airframe applications. The need for more efficient engines will continue to drive development of higher-strength materials that can operate at higher temperatures. PM superalloys are already used in extremely demanding applications, such as turbine discs, because they do not possess the solidification defects inherent in castings and cast and wrought alloys, but stringent processing conditions to control the microstructure and avoid contamination result in high costs. Advances in repair technology, additive manufacturing, and HIP'ing of near-net-shape and net-shape components will enable greater utilization of PM superalloys and stainless steels in aircraft engines.

Medical

The medical market defines a very broad spectrum of sub-markets or segments that include products ranging from cosmetic enhancements, dental, diagnostic equipment, hospital furniture and equipment, implants, medical mobility equipment such as wheelchairs, prostheses, pharmaceuticals and surgical devices, to first-aid and wound-care products. Applications for metal injection molding (MIM) exist in three of the segments, which are identified as dental products, orthopedic products, and other medical devices and equipment. These three general market segments are further divided into product applications that comprise the medical device and diagnostics industry (MD&DI).

Within the MD&DI, two sub-categories or market segments have been identified that have product applications requiring the unique capabilities of the MIM process. These sub-market segments are surgical or procedural devices and implants. Within the surgical or procedural device sub-market segment, product applications for minimally invasive medical procedures can be found. These procedures constitute the greatest growth opportunity for MIM as the devices required to perform these procedures utilize components with high levels of sophistication, demanding material properties, and often are disposable, which drives significant increases in annual-production-volume requirements. Implants can be further categorized into three areas: dental, orthopedic, and cardiac-rhythm management.

The MD&DI worldwide growth rate is estimated to be between 7.5% and 10% annually through 2014. In 2003 an estimated 57 million minimally invasive procedures were performed in the United States, and this number has increased each year thereafter. As surgeries increase in number and complexity, there will continue to be a significant need for new medical devices, which is expected to support continued long-term growth of the market segment.

The orthopedic sector represents the largest portion of the medical device and diagnostic industry, with the highest revenues. Orthopedics also has the largest number of active companies within its sector. With these replacement surgeries, biomaterials demand will grow as patients become more knowledgeable and expect better-performing devices.

Defense

Continuing and emerging threats will drive development of new technologies to meet the detection, protection, mobility, lethality, and energy requirements for defense and homeland security. Advances in security screening, such as X-ray scanning, will continue to make use of tungsten-based collimators and shielding that are processed by PM. Tungsten-based materials will also continue to be used in kinetic-energy penetrators and for maintaining proper weight distribution in missiles and aircraft. The challenges of supplying fuel to remote locations will drive the use of light metals, including PM magnesium, aluminum, and titanium, to reduce fuel consumption. They will also drive the use of alternative sources of energy, which will require components that are prospects for PM. Components with unique combinations of properties may be produced by emerging PM processes, such as spark plasma sintering. Fabrication and repair of parts, both in manufacturing facilities and in the field, may be performed by PM rapid prototyping technologies, such as selective laser sintering and cold spray.

Industrial and Consumer Products

The second-largest combined market for PM encompasses a wide array of applications. New developments will open opportunities for industrial and consumer products. Applications such as telecommunications, computers, home appliance, lawn & garden, farm/off-road equipment, power and hand tools, recreation transportation, sporting goods, and firearms, as well as other high-tech industries, will need component solutions as they provide new products and services to consumers. Increases in living standards throughout the world are expected to expand consumer markets.

TECHNOLOGY DEVELOPMENT PRIORITIES

Continued growth of the PM industry depends on advancements in materials and material properties, processes and manufacturing efficiencies. The three main focus areas of technology priorities for the next decade are high-density PM components, lightweight-materials processing, and electrical and electromagnetic applications.

1. HIGH-DENSITY PM COMPONENTS

Materials:

- ***Development of new materials to replace wrought materials***
  Cost-effective high-density components manufactured from materials with mechanical properties comparable with wrought will be required by engineers.
- ***Enhanced compactibility of powders***
  Powders whose particle characteristics allow high compactibility that enables higher-density components to be formed in the green state are greatly desirable.
- ***New lubricants***
  Typically, 0.5–1.0 weight percent of dry lubricant is added to the powder mixes to aid part ejection after mechanical compaction. However, the low bulk density of typical lubricants displaces valuable space preventing higher compacted green densities. Development of new lubricants that provide equivalent lubricity at much lower added levels would enable higher-density components.
- ***Implantable alloys***
  Development and standardization of PM processes for the generally accepted implantable materials will enable increased acceptance into the medical market.
- ***Granulated micro-powders***
  Granulated micro-powders will enable non-traditional alloy part production. Current research suggests these specialty materials can accelerate sintering times while improving material properties.
- ***Fine powders for MIM and micro-MIM***
  Available technology can typically produce fine powders in normal industrial materials down to approximately 10 microns. Miniaturization is driving components to much smaller sizes requiring finer powders to achieve proper mold flow, surface detail, and mechanical properties.

Processes:

- ***Die-lubrication technology***
  Development of die-wall lubrication technology will enable higher-density components leading to a reduction of potential contaminants and reduced energy consumption by shortening the delube process.
- ***Make high-density processes cost-effective***
  High-density processes are available, such as powder forging and double-press/double-sinter, but are capital and labor intensive.
- ***High-tonnage compaction***
  As high-compactibility powders requiring reduced percentages of lubricant are developed, high-tonnage compacting presses will expand the possible size range of PM components.
- ***3-D forming and compaction technology development***
  While some 3-D consolidation technologies exist, they are not economical for the majority of components. Developing 3-D forming capabilities quickly to enhance today's 2-D technology will have huge implications for market expansion and time-to-market.
- ***High-efficiency, high-temperature, high-capacity furnaces***
  Consistent with the development of high-density compaction technology, improved sintering-furnace capabilities are required. Cost-effective, elevated-temperature >1,260°C (>2,300°F) furnaces will drive improvements in processing components and expand PM further into the domain of wrought materials.
- ***Improved furnace materials, ceramic fixtures/furniture***
  The cost efficiency and productivity of high-temperature sintering can be enhanced by the development of low-cost/long-life furnace fixtures/furniture.

CHALLENGES

Density and residual porosity play a significant role in mechanical properties. Achieving the highest density possible is normally the goal because, as density is pushed higher, the metallurgical properties of the structure approach those of wrought metal, which is considered fully dense. As higher densities become feasible, a larger percentage of the overall fabricated-metal-products market can be captured by the PM industry, as the economic advantages of PM processing techniques are applied to high-density components.

2. PROCESSING OF LIGHTWEIGHT MATERIALS

Materials:

- ***Low-cost lightweight powders***
  Utilization of lightweight metal powders for structural applications has been normally limited by their cost. Typical cost/benefit analysis has generally not favored the PM approach over cast, investment cast, or wrought. Efforts to lower the cost of powder and consolidation technologies are required to enable aluminum, titanium, and magnesium powders and their alloys to gain greater commercial acceptance.

- ***Metal foams***
  Production processes for metal foams have typically targeted specialized applications for which the unique process used by each manufacturer can be fully tested and incorporated. Utilization of metal foams for higher-volume applications will require production processes designed to be likewise testable. Applications in impact absorption and as a substrate for catalytic and battery cells are varied. However, scaling up this process technology is a must.

- ***Titanium powders for conventional PM***
  Production of press-and-sinter titanium components is in its early phase. Characterization of fully alloyed powder which can be pressed and vacuum sintered to acceptable mechanical properties is a clearly needed first step. Standardization of acceptable pressing lubricants that do not contaminate, and identification of critical sintering variables that ensure the structural integrity of the final parts, are key points for market acceptance.

Processes:

- ***Standards, guidelines, and practices***
  Standards, guidelines, and practices are required for the commercialization of both the high-density and conventional press-and-sinter approaches for lightweight metal powders. Typically, these metals and their alloys are very oxidizable and have a high propensity to absorb contaminants during processing.

- ***Minimizing impurities***
  Lightweight metals in their finely divided form (i.e., powders) are very susceptible to pick-up or absorption of interstitial elements such as carbon, nitrogen, and oxygen. These contaminants affect the mechanical characteristics of subsequently formed PM components. Processes and materials to minimize/eliminate these impurities during manufacturing can be key differentiators. This area is ripe for the creation of new intellectual property—companies and institutions can capitalize on research in this novel sphere.

CHALLENGES

One driver for material selection in both the automotive and aerospace industries is weight savings/fuel efficiency. Substitution of lightweight materials for conventional steel and stainless steel components will depend on cost/benefit relationships, and the processing of aluminum, titanium, and other materials. The near-net-shape processing benefit of PM is desirable to the aerospace industry when stringent material requirements are met.

3. ELECTRICAL AND ELECTROMAGNETIC APPLICATIONS

Materials:

- ***High-strength soft magnetic composites***
  Soft magnetic composites that withstand high operating temperatures have been limited for use in static and lower-performance applications due to insufficient mechanical strength and inability to achieve near-full density, which limited their magnetic characteristics. Development of inorganic coatings and binders with both insulating and cross-linking strength are required.

- ***New lubricants***
  Lubricants for compaction are required to form these composites. These lubricants must be used in low quantities to provide maximum green density and green strength.

- ***Non-corrosive conductive materials for fuel cells***
  Research and development of materials engineered with specific properties for fuel-cell applications is required to overcome the intrinsic deficiencies of the current material (high-temperature stability, cost).

- ***Development of enhanced compactibility of powders***
  Powder mixes of specialty-engineered insulated powders, binders, and lubricants minimize the total organic content to achieve maximum densities. Continuing development in this area is required.

Processes:

- ***Standards, guidelines, and practices***
  Standards, guidelines, and practices need to be developed and communicated to motor designers and other design engineers.

- ***Die-lubrication technology***
  Further advances in the development of die-lubrication technologies (delivery methods and lubricants) will enable the required higher-density processing of electrical and electromagnetic components.

- ***High-tonnage compaction***
  Normal compaction pressure for conventional PM components averages 620 MPa (45 tsi). Specialty electromagnetic powders require compaction at tonnages exceeding 830 MPa (60 tsi). Tooling, press platforms, and secondary-handling systems are necessary to fully commercialize this and future advancements of this technology.

CHALLENGES

Soft magnetic/electromagnetic materials development has resulted in soft magnetic composites that withstand high temperatures. Unlike electrical steel sheets, these composite materials have 3-D flux-carrying capabilities for various electromagnetic applications ranging from DC up to 100 kHz. Utilizing 3-D magnetic properties, possibilities emerge for the designer to use new topologies with shape, winding, and assembly solutions beyond today's standard processes, enabling cost-effective benefits such as better performance, reduced size and weight, fewer parts, and lower cost. Electromagnetic applications utilizing these new materials provide environmentally friendly solutions such as compact electric motors and generators, pulse transformers/ignition systems, sensors, fast-switching actuators, inductor cores for power electronics, and inductive components in efficient filter solutions for solar and wind power. It also enables energy storage and transmission concepts such as the Stirling Engine for Micro Combined Heat and Power (microCHP) appliances as well as potential to make Auxiliary Power Units (APUs) for trucks, recreational vehicles, and boats. Today's engineers and designers need to be introduced to the new design possibilities by utilizing PM.

4. OTHER ADVANCEMENTS AND ENABLING TECHNOLOGIES

In addition to the three main focus areas outlined on the preceding pages, the following technology and manufacturing improvements and marketing initiatives were deemed critical to the industry's continued growth.

- Improved machinability techniques (enhancers and additives)
- Means of green-crack detection, including optical
- Continued material standardization and global coordination efforts
- Mold-flow simulation for MIM
- Promotion of industry needs to universities, government, and national labs
- Integration of tool design into software design
- Integration of PM material properties into FEA selection list
- Promotion of modeling efforts to the end user
- Utilization of electronic media for communication, marketing, and market education
- Enhanced promotion of Global PM Property Database
- Exploring outside funding and R&D sources (government/national labs)

Appendix I

PREVIOUS ROADMAP ACHIEVEMENTS 2001-2011

Numerous priorities identified in the 2001 Roadmap were achieved during the past decade. Several of the achievements are listed below. The proceedings of the annual MPIF conferences are a source of reference for information regarding such achievements. Visit Publications at www.mpif.org for more information.

MATERIALS:

Ferrous
- Lean alloys
- Sinter-hardening powders
- Nickel-free, copper-free alloys

Nonferrous and Non-Traditional Materials
- Titanium powders
- Metal matrix composites (MMC) and functionally graded materials (FGM)
- Binders for hardmetals
- Fine and amorphous powders

PROCESSES:

Conventional
- Modeling of compaction & sintering
- Robotics
- Cross-hole compaction
- Machining—green and abrasive

High-Density
- Improved lubricants & die-wall lubrication
- Tooling materials for high-tonnage compaction
- Warm-powder/warm-die compaction

MIM and 3-D Shape Complexity
- Standardization
- Modeling
- Micro MIM advancements
- Rapid prototyping, 3-D printing, laser-engineered net shaping (LENS)

Advanced Technologies
- Highly porous materials
- Layered nanolaminates
- Metal powder cladding
- Net-shape processing of refractory metal alloys

Appendix II

INDUSTRY OVERVIEW

Powder metallurgy is a state-of-the-art metal-forming process used to produce net-shape components. These components are made by mixing elemental or alloy powders and forming the mixture in a mold or die; the resultant shapes are then sintered (heated) in a controlled-atmosphere furnace to bond the particles metallurgically.

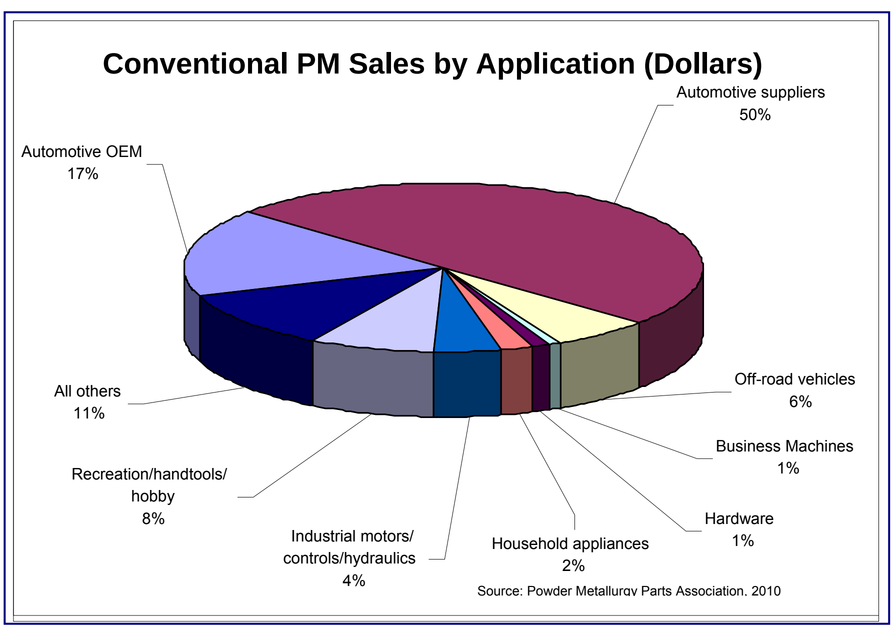
One of the key attributes of the PM process is high material utilization. A near-net-shape metalworking process, PM typically uses more than 97% of the starting raw material in the finished part. Because of this, PM conserves energy and materials and has thus been long-recognized as a green technology.

PM applications fall into three main groups. The first group of applications, the principal one this Roadmap addresses, consists of components for which conventional PM is a cost-effective alternative to machined components, castings, and forgings. Key markets in this group include automotive, electrical and electromagnetic, alternative energy, aerospace, defense, medical, and industrial and consumer products.

The second group consists of applications in which loose powders or powder mixtures are used for welding, joining, and spray coating for the fabrication, repair, and surface texturing industries.

The third group consists of components difficult to make by any other production method, such as cutting tools and other components made from tungsten, tungsten carbide, or molybdenum. In addition, porous bearings, filters, and many types of hard and soft magnetic components are also produced exclusively by the PM process.

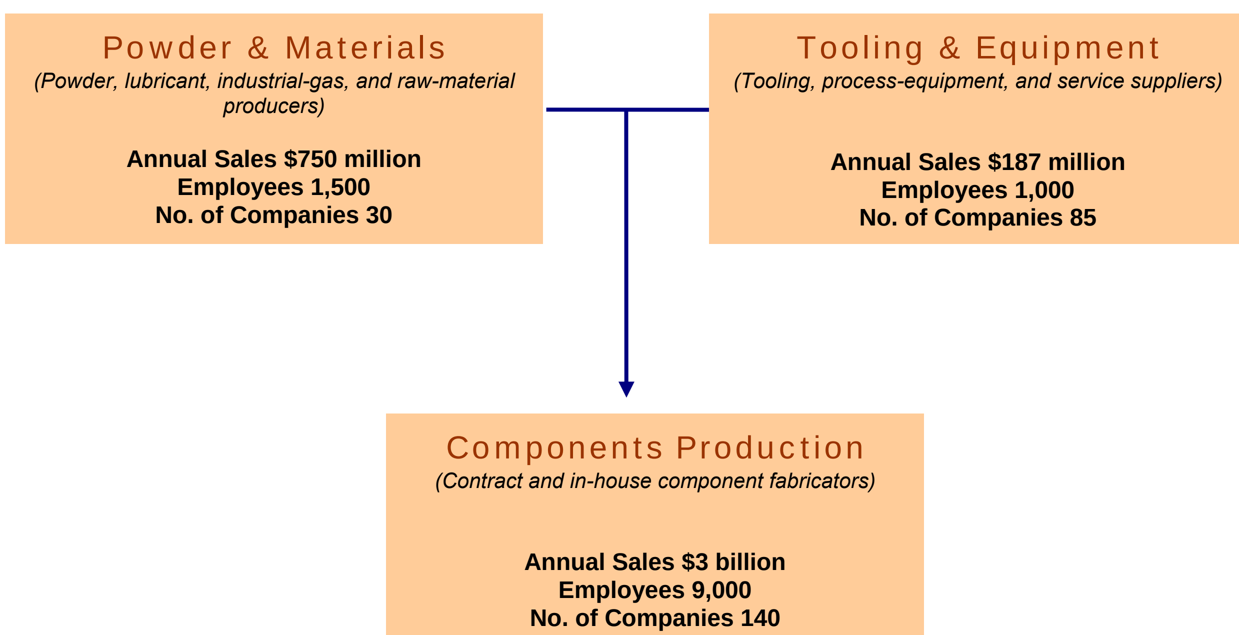
Estimated sales from all three sectors in North America total over $7.0 billion, with employment exceeding 25,000 people. The majority of PM companies are small; 90 percent of the firms are classified as small businesses by U.S. government standards.



The success of the PM industry is directly related to the health of the automotive industry. Currently that sector consumes 70+ percent of all ferrous PM components produced. It has been estimated that there are approximately 350 PM automotive component applications totaling about 1,000 discrete pieces. The number of applications is steadily rising as PM is increasingly viewed as an effective alternative to machined or cast parts. Meeting automotive needs is critical to the continued success of the PM industry and is central to the industry's vision.

PM's value has been derived from its net-shape capabilities, high material-utilization rates, and minimal energy-input requirements. Coupled with environmentally friendly operations and use of scrap for the source of powder materials, the sustainable nature of PM technology provides a positive contrast to other metal-forming technologies. Often the manufacture of a PM component requires fewer steps and offers greater material choices, as well as unique properties unavailable with other metal processing techniques. PM can provide sustainable manufacturing benefits from the point of view of either a value-added product feature, such as lighter-weight auto components, or process efficiency.

Structural-Component Segment of the North American Conventional PM Industry

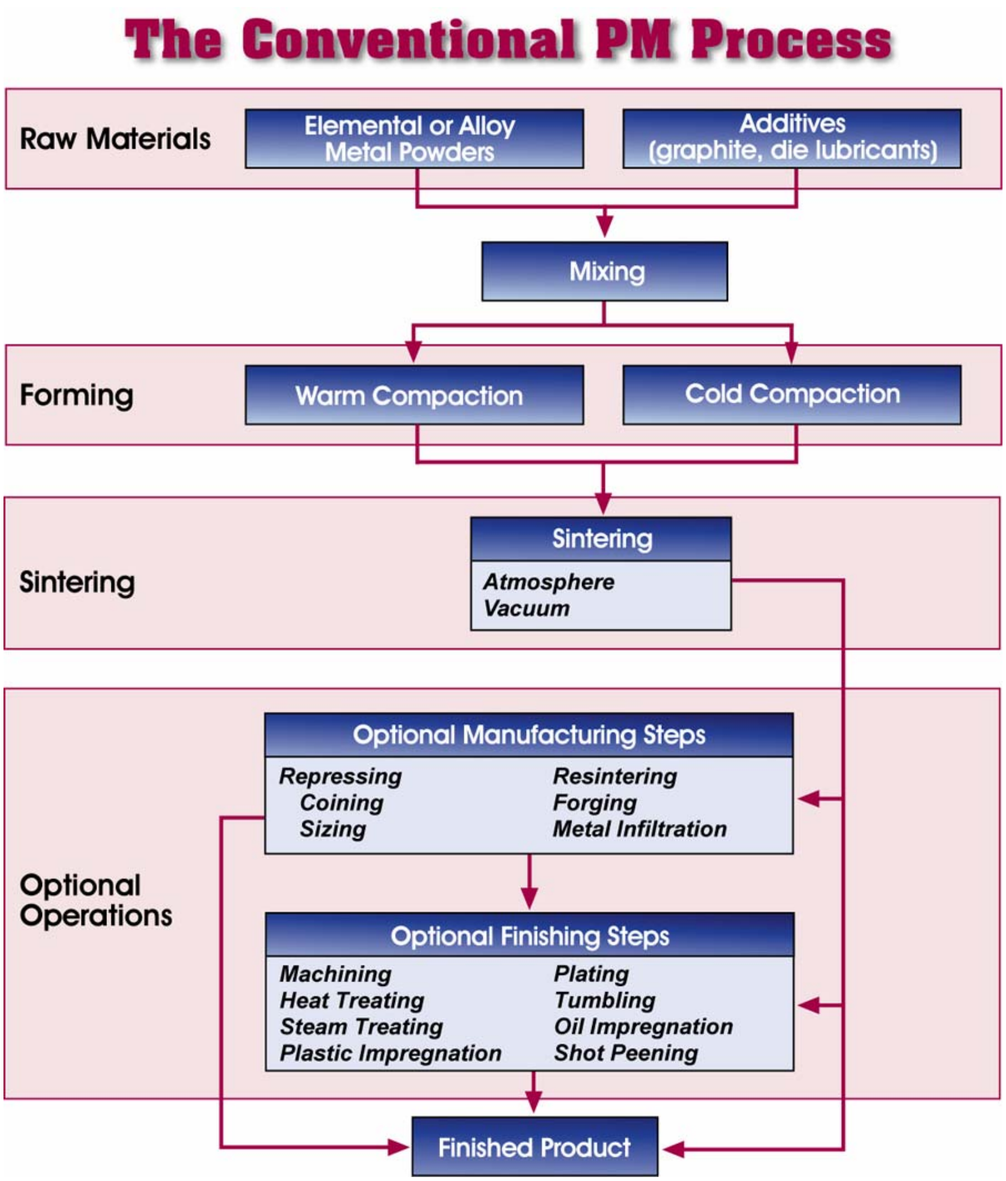


Appendix III

THE PM PROCESS

PM's value is derived from reduced energy consumption, efficient use of raw materials, and lesser labor intensity than other competitive metal-working industries. The process is capable of producing simple to complex components and has created components not capable of being formed with other technologies. Most PM parts weigh less than 2.27 kg (5 lbs.), although parts weighing as much as 15.89 kg (35 lbs.) can be fabricated in conventional PM equipment.

The three basic steps for producing parts by the conventional PM process are mixing, compacting, and sintering.



Flow chart of the conventional PM process used to manufacture structural components

Mixing

Elemental, partially alloyed, or prealloyed metal powders are first mixed with lubricants or other alloy additions to produce a homogeneous mixture of ingredients. These additives may help impart machinability, wear resistance, or lubricity to the base-alloy composition.

Compacting

A controlled amount of mixed powder is automatically gravity fed into a precision die and is compacted, usually at room temperature, at pressures as low as 138 MPa (10 tsi) or as high as 965 MPa (70 tsi) depending on the density requirements of the part and the compressibility of the powder being pressed.

Compacting the loose powder produces a “green” compact that has shape of the finished part when ejected from the die and sufficient strength for in-process handling and transport to a sintering furnace. Typical compacting techniques use rigid dies set into special mechanical or hydraulic presses.

Tool sets are made of either hardened steel and/or carbides, and consists of a die body or mold, an upper and a lower punch and, in some cases, one or more core rods. The die receives a charge of powder, delivered to the cavity by a feedshoe; the volume of powder is controlled by the relative positions of the lower punch in the die. After filling, the feedshoe withdraws as the upper and lower punches cycle and compress the powder. The relative motion upwards of the lower punch ejects the compacted component at the end of the cycle. The cycle begins again with the advance of the feedshoe to refill the die cavity and simultaneously nudge the previously compacted component from the die-set surface. Multiple punches with separate actions can form component features. Modern, computer numerically controlled (CNC) compaction presses provide greater precision and control for complex shapes by continuously monitoring and adjusting positions and speeds through a feedback loop.

Sintering

In the typical sintering step, the green compact moves through a controlled-atmosphere furnace. The parts are heated to a temperature below the melting point of the base metal, held at the sintering temperature, and then cooled as the part exits the furnace. Sintered parts have the strength levels to meet functional requirements of the components.

PM parts are generally ready for use after sintering. However, to provide special properties or features, the components can be repressed, impregnated, machined, tumbled, plated, or heat treated.

Appendix IV

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The process of updating this PM Industry Roadmap was made possible through efforts on the part of many industry individuals over a period of 18 months.

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MPIF is a federation formed by the PM industry to advance the interests of the metal powder producing and consuming industries. It is a federation of trade associations, all concerned with some aspect of powder metallurgy, metal powders, or particulate materials—Powder Metallurgy Parts Association, Metal Powder Producers Association, Powder Metallurgy Equipment Association, Metal Injection Molding Association, Refractory Metals Association, and Isostatic Pressing Association.

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