DESIGN GUIDE

IS MIM RIGHT FOR YOUR PARTS?

• Automotive • Aeronautics • Computers/Technology • Recreation
• Firearms/Defense • Dental/Orthodontics • Medical

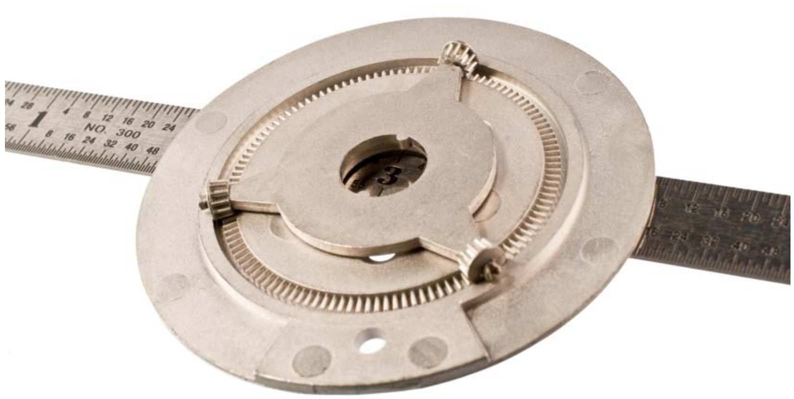
A DESIGN GUIDE FOR MIM – METAL INJECTION MOLDING

Introduction: What is MIM?

Metal powder injection molding (MIM) is a new and revolutionary shaping process focused on forming complex-shaped, high-performance components in large production quantities from metals, or even cermets and ceramics. It is a hybrid between plastic molding and sintered powders. It is successful as a production process when four main considerations are satisfied:

1) low cost versus competitive fabrication routes
2) high performance with competitive properties
3) high shape complexity in a smaller component
4) large production quantities.

Most of this design guide is organized around detailing and quantifying these attributes. But as a starting point, note the complex shape possible with MIM. It is aligned with the MIM process because of its complex geometry that would have been cost prohibitive in other forming methods. The detail of the gear faces combined with the harsh high heat environment necessitated a high performance alloy. MIM also afforded the designers to incorporate the assembly features thus reducing the total number of components needed in the assembly



The concept of using injection molding plastic equipment to shape a metal excites many design engineers, especially when they learn the final properties are the same as with most other metalworking processes. MIM succeeds because there is little material loss; typically 98% of the purchased raw material ends up in final products. Further MIM enables shape complexity in materials that are often difficult to fabricate by other processes, such as composites (W-Cu), electronic alloys (glass-metal sealing alloys), hard materials (tool steel), stainless steels, nickel-base superalloys, titanium, and tungsten.

The MIM design process combines decisions on the material, component geometry, component function, and fabrication process. It is important to balance both economic and technical considerations.

Most common engineering alloys are possible by MIM, but about 30 alloys dominate the applications. The most popular alloys are surgical stainless steel (commonly called 17-4 PH, or American Iron and Steel Institute 630 or AISI 630) and austenitic stainless steels (AISI 304L and AISI 316L). After injection molding, the polymeric binder is extracted and the particles are subjected to a high temperature heat treatment termed sintering. During sintering the capillary forces between the small particles densify the structure to give a slightly shrunken component that is essentially full density with tensile and hardness properties equivalent to handbook values.

Alloys can be formed by mixing elemental powders to match the desired alloy, for example iron, nickel and chromium to form a stainless steel. The powders homogenize during sintering to deliver the alloy composition and properties. Another approach is to use prealloyed powder where each particle contains all of the elements. Ferrous alloys are popular by MIM, and about 60% of the commercial activity is in stainless steels. Components formed by MIM are widely used in dental orthodontics, portable computers, automotive engines, surgical instruments, electronic packages, watches, hand tools, firearms, sporting devices, and cellular telephones.

One of the keys to economic success is to apply MIM to complicated geometries, those that would require extensive machining. Further gains come by adding cores, holes, or other mass reduction features, the opposite to the situation in a machined component. Thus, MIM excels versus other fabrication approaches when the component complexity is high and performance demands require excellent properties. It wins against casting since it has better dimensional control and a smoother surface finish. Unlike machining, MIM is best applied to large production quantities. Accordingly, several situations have reached production quantities in excess of ten million parts per year.

Process Essentials

Greatest gains come when MIM is used to form structures with properties not possible from plastics. It is essentially a three-step process involving:

- formulation of **feedstock** from appropriate metal powders and polymers
- **molding** of that feedstock into tooling that is designed for the final part and includes dilation of the size in anticipation of sintering shrinkage
- **thermal** processing of the shaped part to remove the polymer (debind) and sinter the powder.

The latter step might be accomplished in a single cycle or in two separate steps of first debinding to remove the polymer followed by sintering.

Most of the metal or ceramic powders used in MIM are between 1 and 40 µm. For comparison, human hair is typically 100 µm wide. The powder is mixed with a plastic binder. The typical ratio is about 60 vol. % powder, requiring then about 40 vol. % binders. Depending on the metal powder (aluminum is light, tungsten is heavy), a steel or stainless steel mixture constitutes about 94% powder by weight, but for low density powders such as aluminum this is 86% powder and for high density powders such as tungsten this is 97% powder. The binders melt at relatively low temperatures to allow easy mixing and molding. The combination of powder and binder is termed feedstock, and feedstock is available from about a dozen suppliers and many firms also mix feedstock to their own specifications.

The heart of production is molding, where the heated feedstock is shaped in a custom designed tool. Prior to molding the powder-binder feedstock is heated inside the injection molding machine to melt the polymer phase. The molding machine rapidly presses the molten feedstock mixture into the mold cavity to avoid any premature freezing. During this molding step the powder remains unaffected by the molten binder, since the peak temperature is far below the powder’s melting temperature. After injection into the mold cavity, the pressurized feedstock cools to solidify the polymer, thereby freezing the particles into the desired shape. Cooling is usually the slow step, so molding cycles often are 20 to 45 seconds. After extraction from the mold, the polymer portion is removed by heat, solvents, or catalysts without disturbing the shaped powder - a process known as debinding. The final portion of the polymer decomposes while heating the shaped body to the sintering temperature.

Sintering is a particle bonding heat treatment that naturally densifies packed powders when they are heated to a temperature where atomic motion is active. For most powders, sintering starts well below the melting temperature. Besides considerable strengthening, one common result of sintering small powders is component densification; the sintered component is smaller than the molded component. Indeed, in MIM the final component is about 15% smaller in each dimension due to annihilation of the space initially filled with binder. The attached picture shows before and after images of a molded component to illustrate sintering shrinkage. After sintering there is no evidence of the initial powders or polymers. Thus, performance attributes of MIM products rival properties cited in engineering handbooks.

Secondary steps after sintering are very much the same as applied to all metals. The components can be heat treated, electroplated, drilled and tapped with threads, and welded. After sintering there is nothing different in the MIM material versus standard metallurgical treatments; there are no artifacts from the powders. Thus, MIM competes with investment casting and machining. It is most competitive when used to form complicated and durable components, especially when the components require properties better than attained with die casting. Further, MIM is best suited for mass production and is commonly applied to production quantities over 200,000 parts per year. However, applications as low as 5,000 units per year may sometimes be cost justified. Each application must be reviewed individually for economic viability.

Where MIM Differs from PM

Some engineers confuse MIM with traditional press-sinter powder metallurgy (PM). The standard powder metallurgy forming step relies on vertical axis compaction to press a coarse powder into compact. The pressing route is the same as used to form pharmaceuticals pills. Die compaction is best at forming squat shapes that are easily ejected from the tooling. The ejection step requires the sides be parallel, a restriction in geometry not seen in MIM. Thus, in MIM undercuts and holes are possible perpendicular to the main axis, as illustrated by this MIM component.

A major difference in the two technologies is in the final density and final properties. Because of friction between the powder and tooling, pressed powder is non-uniform. If sintered in a high temperature MIM sintering cycle, the component would warp, like a potato chip. Thus, PM parts are lightly sintered and retain considerable porosity and have significant property degradations.

A critical difference is in dimensional control. MIM components are formed with uniform density and the scatter in final component mass and dimensions is small. For PM the standard protocol is to use larger powders versus MIM and to sinter at lower temperatures for shorter times to avoid distortion during sintering densification, resulting in lower properties. As an example, MIM strengths are about two-fold higher than PM, fatigue strength is more three-fold that of PM, and impact toughness is eight-fold higher when compared to PM. Sometimes the marketplace also tells the story. While MIM is expanding rapidly, over the last ten years PM has seen significant contraction. Between year 2000 and 2011, North American press-sinter PM shrank by 20% while MIM more than tripled.

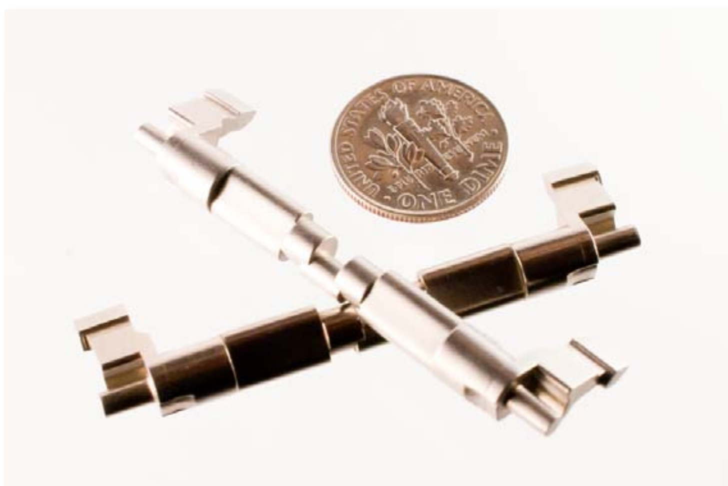
Unique Aspects of MIM

MIM produces a wide range of high-performance, complex-shaped components that require little or no machining. Because of the high final density, MIM products have properties that are equivalent to those gained with other fabrication routes. There is exceptional material flexibility, in that the same equipment can be used to produce metals (steels, stainless steels, tungsten composites, titanium, copper), ceramics (namely alumina and zirconia, but some silicon nitride too), and cermets (tungsten carbide and other wear materials).

Secondary benefits include high equipment productivity, high material utilization, good surface finish, and good tolerances. For example, producing both internal and external threads in the molded component is an option, thereby avoiding machining. Also, serrations, waffle patterns, part identification numbers, and insignias can be molded directly into the component. One example is shown where serrations for gripping are molded directly into the component. Controlled pores are possible, and even stratified pores or phases are possible to provide custom functionality.

- MIM provides a means to form large production quantities. Some components are produced at rates exceeding 200,000 per day. On the other hand, small production runs are possible, with as few as 5,000 parts per year. However, as with all technologies, the essence centers on economics.

- MIM is cost advantageous for complex shapes when compared with options such as machining, casting, or forging. This advantage comes from the elimination of manufacturing steps. Also, the process has little material loss, a point especially important for costly raw materials such as refractory metals, titanium, superalloys, and precious metals.
- MIM has gained much credibility and achieved broad industrial acceptance. Shown here are a few recent examples of MIM components from Smith Metal Products.



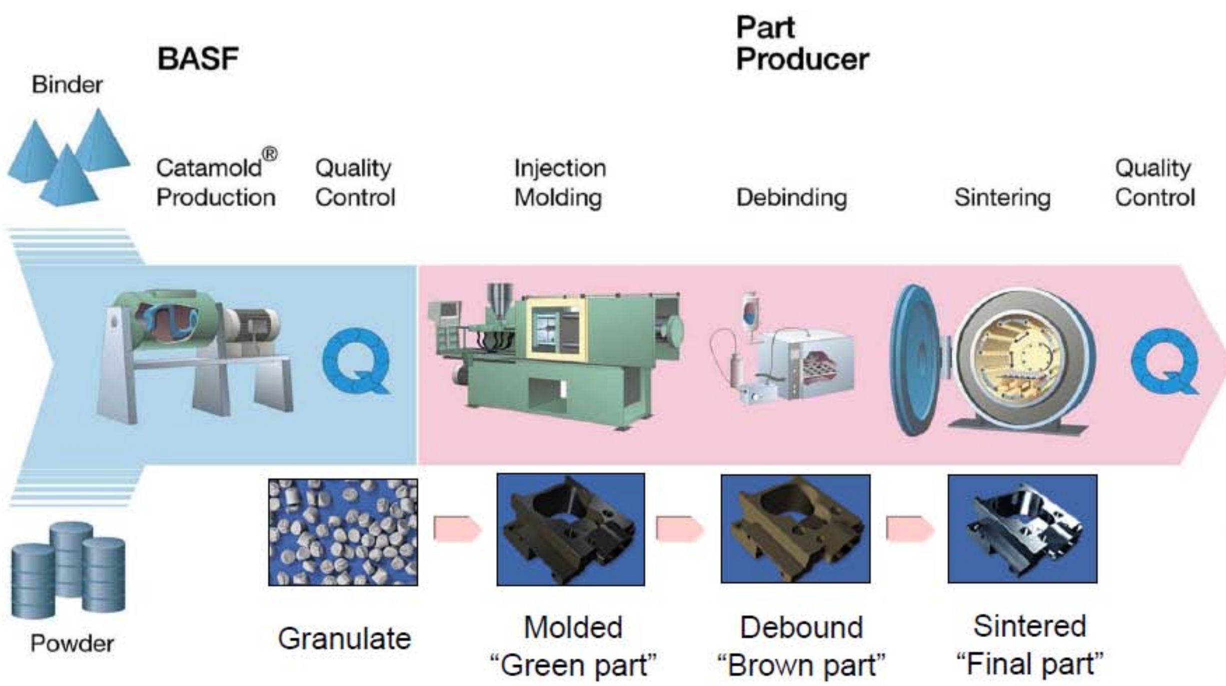
Contrast with Other Technologies

Although MIM traces to plastic molding, it is significantly different in materials, markets, and properties. A large difference between MIM and plastic molding relate to the properties; metals are conductive, magnetic, strong, stiff, tough, and can operate at temperatures far over the melting range of most polymers. For example, the useful strength of polyethylene formed by plastic molding is less than 20 MPa (3 ksi), while MIM steels are stronger by a factor of 20 to 100. Only fiber reinforced specialty polymer systems (such as Kevlar-epoxy) compete at these property levels (at high costs). Although both technologies seem similar, the engineering properties possible by MIM are outside the reach of plastics. However, metals are higher in density when compared to plastics.

Process Options

Overview: Engineers think of injection molding as a plastic forming technology, using polyethylene, polystyrene, glass-filled nylon, and similar materials. Metals and ceramics have several desirable properties when compared with plastics. They are stronger, tougher, stiffer, and offer significant latitude in electrical and thermal conductivity, magnetic response, wear behavior, and operate to high temperatures. MIM is a synergistic combination of the performance properties associated with inorganic materials and injection molding associated with plastics. Most applications for powder injection molding are in metals, especially stainless steels.

In MIM, small powders are molded in the desired shape using a thermoplastic binder. Binders can be as simple as paraffin wax (candle wax), but usually are a mixture of several engineering polymers. The binder softens and melts on heating and then freezes in the mold to hold the particles into the desired shape. After molding, the shaped powder is sintered to attain the target properties. A schematic of the Smith process is illustrated here. The polymeric binder bonds the particles during the shaping process and is extracted as the particles are heated. Once the polymer is extracted, the porous powder structure looks like the molded shape, but it is weak. However, when the powder is heated to a high temperature, the particles bond and densify due to capillary attraction, in what is called sintering. There is a tremendous strength gain in sintering, to the point that the sintered solid is essentially indistinguishable in strength from wrought metal. So in MIM the plastic or polymer is only a transient phase, added to help the metal particles flow and fill out the mold.



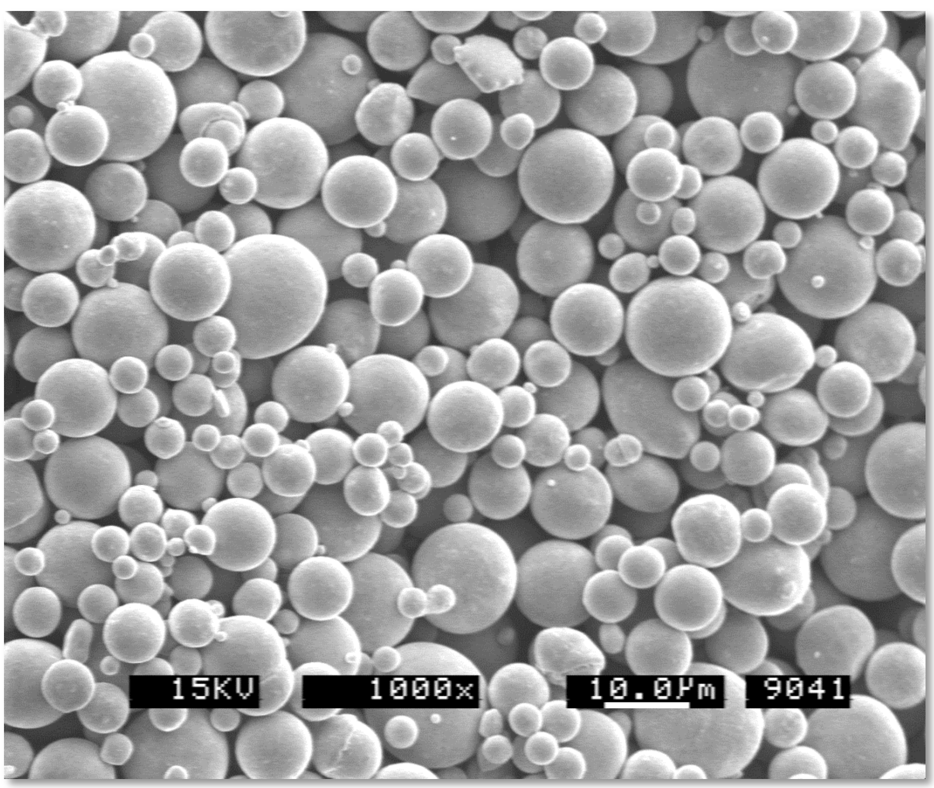
The MIM process has many variants, reflecting different combinations of powders, binders, molding techniques, debinding routes, and sintering furnaces. However, all variants share three technology areas:

- **feedstock**; powders, binders, mixing
- **molding**; rheology, tool design, machine operation
- **thermal processing**; debinding, sintering, heat treatment.

Powder Options

The powders used for MIM are generally small, round if not spherical, and deagglomerated. Already the technology has worked with over 1000 different alloys, but a few are dominant – 17-4 PH stainless steel (AISI 630), 316L stainless steel, and several other stainless, steel, cobalt-chromium, copper, and titanium compositions. In most cases the median particle size is about 10 to 20 µm, but smaller powders are available if needed to form microscopic features.

Shown below is a high magnification scanning electron micrograph of a typical stainless steel powder used in MIM; note the marker showing 10 µm, indicating most of the particles are smaller than this size.



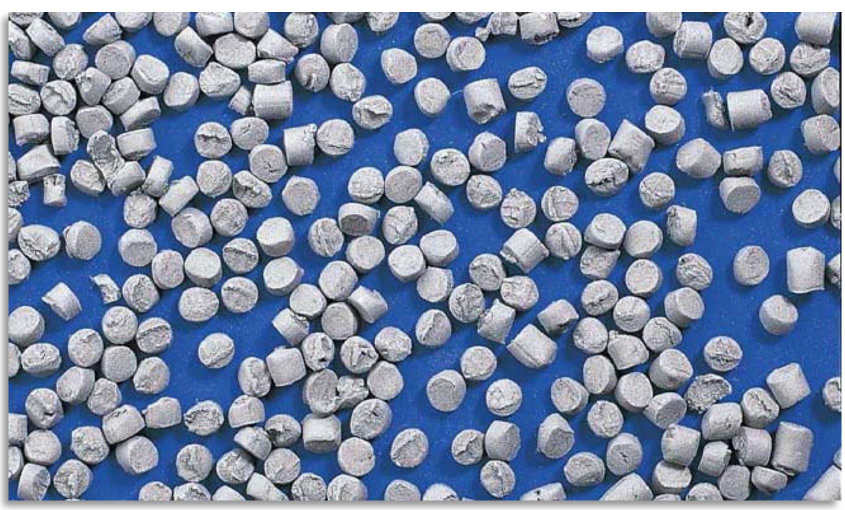
Alloys are most typical and three options exist in MIM. One is to mix the chemical ingredients as powders, say iron-nickel-chromium to form a bulk composition, relying in atomic diffusion during sintering to homogenize the ingredients, termed mixed elemental powder. A different route is to form molten alloy and to atomize the alloy into individual particles, where each particle is of the same alloy composition, termed prealloyed powder. A hybrid relies on a mixture of high alloy powder mixed with elemental powders, for example iron mixed with atomized nickel-chromium-iron particles, termed master alloy. Although more costly, the prealloy route is most typical in MIM.

Feedstock Options

Feedstock then is a mixture of the powder and binder as homogeneous paste that can be molded. The tool cavity is designed around the feedstock, and includes consideration of the binder melting temperature, particle size of the powder, feedstock viscosity, and feedstock strength.

Best molding is attained when the hot feedstock viscosity is near 100 Pa·s (1000 poise). As a benchmark, this is thicker than most paints (which are small particles such as titania dispersed in acrylic emulsion binder) and more like toothpaste (which also consists of small oxides particles in a binder formed from cellulose or gum dissolved in water), but not like cold ice cream. A typical feedstock is formed into pellets that are properly formulated to directly feed into the injection molding machine.

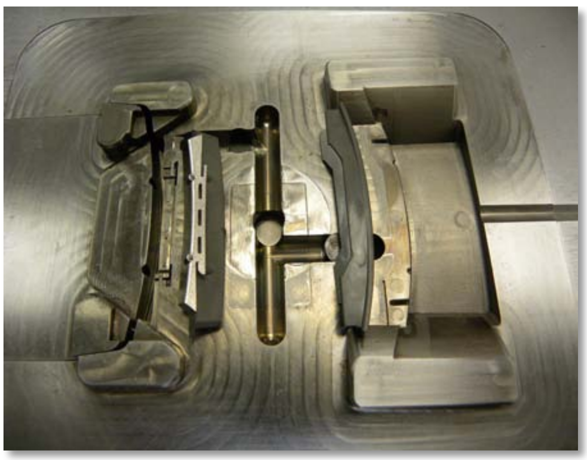
Shown below is a picture of typical feedstock pellets.



It is possible to purchase premixed feedstock for common alloys, but it is also possible to formulate custom mixtures to adjust moldability, alloying, or other features. The situation is comparable to buying premixed cookie dough versus making cookies from scratch. There are merits to both approaches. More than a dozen feedstock suppliers exist, each with a range of materials.

Tooling for MIM

The tool cavity or mold for MIM is constructed as an enlargement of the final part. The space taken up by binder in the feedstock is annihilated by sintering. This is evident in that the final component is usually about 15% smaller than the tool cavity.



1 + 1 "Family" mold, ejector side of tool.

Left: Sintered part to the right of the cavity.

Right: Green part to the left of the cavity.

Although tool dimensions are expanded to allow for sintering shrinkage, angles are generally preserved. However, mold design is much more complicated than simply dilating the dimensions. Many critical decisions are required on features that include the following:

- parting line location; where will the mold open to extract the component
- gate size and location; how will the feedstock enter the mold
- taper or draft; can a small taper be included to ease ejection from the tooling
- ejector pins; where and how many ejector pins are required for part ejection
- slides; are tool motions required to add features perpendicular to the parting line
- motions; for example are threads to be added using unscrewing motions.

Molds for MIM are constructed in a manner similar to how plastic injection tooling is formed, so MIM vendors rely on the same tool and die industry. Mold design and construction can be a slow step. It is common to see tool design and tool construction run several weeks. In practice most tool sets are first created with outer dimensions set to the lower end of the component tolerance band and the inner dimensions set to the high end. This "steel safe" approach allows for final mold size adjustments after first test pieces are sintered. Once precise shrinkage factors for each dimension are known, the final mold cavity dimensions are modified by final machining.

Within a mold, the number of cavities ranges from 1 on up. A single cavity tool is satisfactory for low production quantities. The lowest project cost depends on the number of parts per year to be produced. In rough terms here are some typical break points:

- below 100,000 parts per year - 1 cavity.
- 50,000 – 250,000 parts per year – 2 cavities.
- 250,000 – 500,000 parts per year - 4 cavities.
- 500,000 – 1,000,000 parts per year – 8 cavities.
- 1,000,000 – 5,000,000 parts per year – 12 or 16 cavities
- 5,000,000 or more parts per year – 16, 32 cavities or multiple lower cavity count tools.
-

These are not fixed rules, since many factors are involved; for example the maximum clamping force on the molding machine is such a factor. In addition if there are very close tolerance and dimensional requirements on the components multiple lower cavity count tools may be a better path to keep process capability and controls as tight as possible.

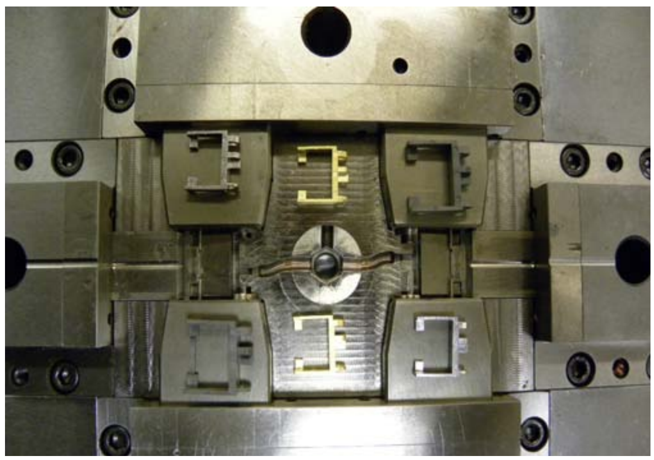
MIM tooling is often hardened steel, such as P20. When heat treated, this steel easily resists wear. Harder tool steels are used for tooling for high production quantity situations. It is possible to have from 100,000 to 2,000,000 shots between mold refurbishing treatments, depending on the powder and component. Ceramic particles are very hard and angular, a combination that requires mold refurbishing as often as every 50,000 shots.

Molding

Molding converts the feedstock into a defined shape. The feedstock granules are loaded into the hopper of the molding machine such as shown here. It is essentially the same as used for plastic injection molding. For high production components, a robot system is used for handling and staging for debinding and sintering.

The molder conveys the feedstock pellets into a heated barrel with an internal screw for stirring, compressing, and melting the feedstock. A nozzle at the end of the barrel butts against the mold during filling. The mold is clamped closed. It is important for the screw to heat, melt, and stir the feedstock to ensure homogeneity and no trapped air bubbles. The screw has a taper that compresses the hot feedstock to squeeze out any trapped air.

When ready to fill the mold, the hot feedstock is rammed into the mold cavity. In molding, the feedstock flows to fill out the cavity. Once the mold cavity is filled, the feedstock is cooled to freeze the powder-binder mixture into the desired shape. When sufficiently cool, the rigid component is ejected from the mold and the molding cycle repeated, typically once every twenty to forty-five seconds.



Two Cavity mold with "Green" parts (upper right and lower left), Sintered parts (upper left and lower right), and Gold Plated finished parts (upper and lower center).

During molding, the molten feedstock flows into the cavity from the gate toward the vent, which allows air to escape from the mold. Vent size and location is part of the tool design, and an improperly designed tool will lead to trapped air pockets in the molded shape.

Peak temperatures in molding depend on the binder melting temperature, but are often below about 200°C or 400°F. The tooling is cooler than the feedstock, so the feedstock undergoes a progressive viscosity increase as it flows into the mold and gives up heat to the tooling. Cooling increases flow resistance so sophisticated molding relies on high pressures to rapidly fill the cavity. The peak molding pressure varies with the geometry, but might range from 1.4 MPa to 60 MPa (200 to 8,500 psi).

Multiple cavity molding is used to increase productivity, and up to 64-cavity molds are used in MIM production. Multiple cavity molding presents some balancing and control problems; hence, the tradeoff between the molding problems, tooling cost, and machine productivity often results in a compromise of about two or four-cavity molds.

Debinding

After ejection from the mold, the binder is removed from the component in a process called debinding. Prior to debinding it is common to call the shaped part "green". Binder extraction is a slow process that decomposes the binder without disturbing the particles. Usually a small quantity of binder is used to hold the particles in place until sintering starts. Any final binder evaporates as the porous powder structure approaches the sintering temperature. A common debinding cycle utilizing solvent or thermal debinding might require 12 hours for the combined heating, hold, and cooling. During processing the components are placed on trays to provide support and to enable transport. Sometimes custom trays are necessary to maintain flatness and/or dimensional stability during debinding and sintering.

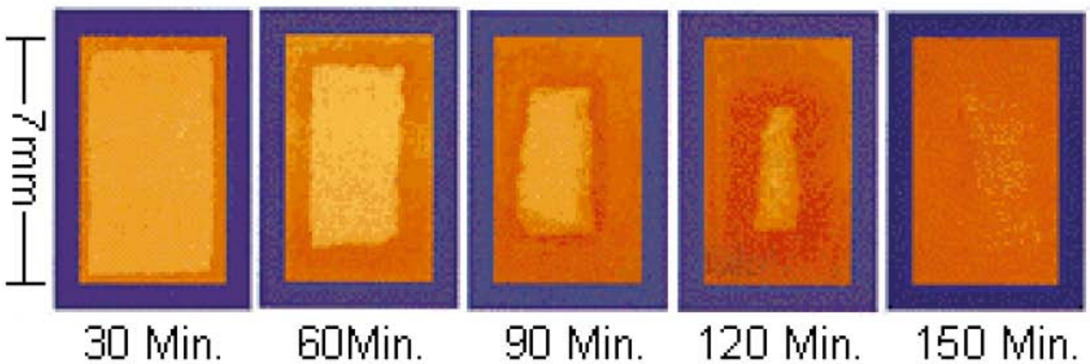
Catalytic Batch Debinding at Smith

A wide variety of debinding options exist, and selection of the best route depends on the binder system, component shape, and material. Thus, there is no single cycle or processing time. Unfortunately, early MIM firms relied on hazardous chlorinated hydrocarbons such as carbon tetrachloride. However, in recent years most of the MIM production has moved to more eco-friendly cycles and processes.

An option practiced at Smith is catalytic phase erosion of a polyacetal binder. The polyacetal binder is attacked depolymerized during heating. Feedstock for the catalytic debinding route is provided by several firms, including BASF.

- Fastest process available (1 - 2 mm/h)
- Excellent green strength & stiffness
- No deformation
- Process allows for fully continuous ovens (30 - 300 t)
- Most robust, repeatable system available

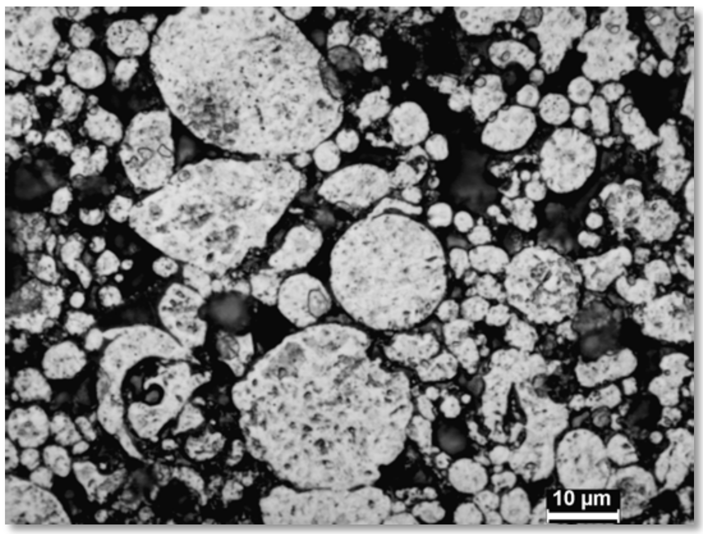
→ Improved dimensional control

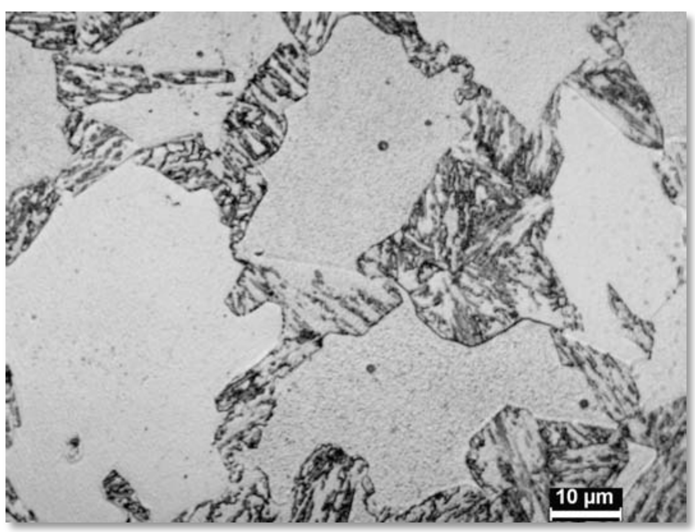


In debinding, the erosion of the binder is from the outside surface. If the system is heated rapidly, then internal vapor pockets form and create blow holes, blisters, or even miniature volcanic eruptions. Generally, slow heating to 600°C (1112°F) over several hours in a protective atmosphere is most effective. The time for debinding increases as the section thickness increases. For most metal powders and binders, a rule of thumb is that debinding can penetrate about 2 mm per hour (0.08 inch per hour). Since the erosion is from both the front and back (or top and bottom) surfaces, the time for debinding is approximated by considering the thickest half-section. For example, a wall that is 10 mm across requires heating at 1°C/min (1.8°F/min) to at least 450°C (842°F) with a hold of 2.5 h (5 mm divided by 2 mm/h) as long as both surfaces can be accessed during debinding. This says that heating requires about 6 hours, with a peak hold of 2.5 hours, and about 6 to 8 hours of cooling time, so a 12 to 24 hour cycle is typical.

Sintering

Final polymer extraction occurs during sintering. Sintering was used thousands of years ago to harden bricks or pottery by firing the shaped "green" ceramic body. The same idea is applied in MIM. Sintering changes a powder structure into a solid structure. This is illustrated below using optical microstructures taken from a 17-4 PH stainless steel powder during heating to 1000°C (1832°F) and then 1365°C (2460°F). In these pictures, the pore space previously occupied by binder appears black, and it disappears during heating.





Clearly sintering densifies the powder by removing the void space previously occupied by the binder. When properly performed, the sintered microstructure shows no evidence of the original powders and little porosity. The typical sintering shrinkage is from 12 to 18% on each dimension, nominally 15%, so the molded component is oversized to deliver the desired final dimensions.

Batch Versus Continuous

Sintering is performed in a protective atmosphere or vacuum. Sintering furnaces are a major capital cost in MIM. Usually they are custom fabricated in size, atmosphere, capacity, and cycles depending on binder, component size, and peak temperatures. Batch furnaces are used for smaller production quantities and usually reach peak temperatures from 1400 to 1600°C (2552 to 2912°F). Common protective atmospheres are hydrogen, nitrogen, or argon. Many production sintering units are vacuum batch furnaces.

For larger production quantities it is appropriate to move to continuous furnaces, where sintering and debinding are combined into a single device with a sequence of zones that require from 6 to 24 hours to traverse. These too can reach peak temperatures of 1600°C (2912°F). The central zones are profiled to hold precise temperatures while the components move via a pusher plate conveyor mechanism from the cold entry to where they are cooled prior to exit.

Smith Batch Furnaces

Smith Continuous Debind / Sintering Furnace

Precise final dimensions rely on uniform molding and uniform heating during sintering. When MIM is properly executed, the sintered compact has the shape and precision of an injection molded plastic, but the sintered metal delivers performance levels unattainable with plastics. This is because the sintered structure is fully dense, with no residue from the original powder. Further, proper cooling in the furnace can impart a heat treatment to the structure to induce excellent mechanical properties. The sintered product may be further densified, coined, plated, etched, or machined to complete the fabrication process.

Secondary Operations

After the component is sintered, additional changes in size, shape, surface finish, or heat treatment are possible. The material is essentially in the annealed condition after sintering and there is no significant difference in secondary operations from any other manufacturing route; the response is the same as with wrought materials.
Common secondary operation steps include the following:

- *coining or cold deformation* – A sintered compact is forced to conform to a rigid mandrel or substrate to straighten or ensure desired flatness or dimensions. This allows for proper sizing of features with a reduced spread in dimensions.
- *hot deformation* – The sintered compact is heated and deformed by a rapid forging stoke to ensure proper size and density. For a steel, the sintered strength jumps from 500 MPa to 720 MPa after hot deformation.
- *machining* – All common machining operations are applied to sintered MIM components – to add threads, undercuts, grooves, or special features difficult or expensive to place in the tooling.
- *heat treatment* – Sintering leaves the material in an annealed condition. For low carbon ferrous alloys, this is of little consequence, but for high carbon levels it is possible to adjust hardness and other properties via sintering heat treatment. In some cases it is possible to incorporate the heat treatment into the sintering cooling cycle, but more often it is performed as a second step. Precipitation hardened stainless steels require cycles of heat and hold to properly optimize the mechanical properties.
- *surface carburization* – Carbon is important to attaining high strengths in steels. A high surface hardness is attained with carbon surface additions using a heating cycle with an atmosphere containing methane. Surface carburization cycles result in some loss of dimensional precision, so trade-off is required between surface hardness due to the addition of carbon (carburization) and dimensional accuracy.
- *joining* – Like other metallic components, MIM components are joined by welding, brazing, or even adhesive techniques. For the most part, MIM materials behave the same as standard metals. Laser welding proves very effective with MIM stainless steels.
- *surface treatments* - Surface treatments such as polishing, coating, painting, cleaning, anodizing, plating, sealing, and laser glazing are all applied to MIM components. Surface hardening treatments sustain a tough core with a hard surface. Electroplating is used for either improved aesthetics or corrosion resistance. Nickel electroplate is a favorite on instrumentation, firearm, or magnetic components.

A key point is that after sintering, there is no behavior difference for a MIM component versus any of the other manufacturing routes. Consequently, no special handling procedures or steps are required in the secondary operations for MIM parts.

Vendor Differences

There is no standard MIM process; thus, variations exist between vendors. The differences come from the many choices on powders, binders, tool design, processing cycles, equipment design and operation, impurities, and post-sintering treatments. Part geometry can also drive specialized processes. Property scatter is small within a MIM operation, often less than seen in forgings or castings. However, the differences in details at each MIM company leads to possibly large cross-industry scatter.

For example stainless steels can absorb nitrogen in sintering and this tends to increase strength, but also reduces ductility to half the value seen with hydrogen sintering. If slowly cooled, nitrogen in a stainless reacts to form a compound that leads to significant corrosion problems. Hence, depending on the processing atmosphere and final density there will be property differences; one vendor will have high strength and low corrosion resistance and another will have high ductility and good corrosion resistance.

The differences between MIM vendors generally are as follows:

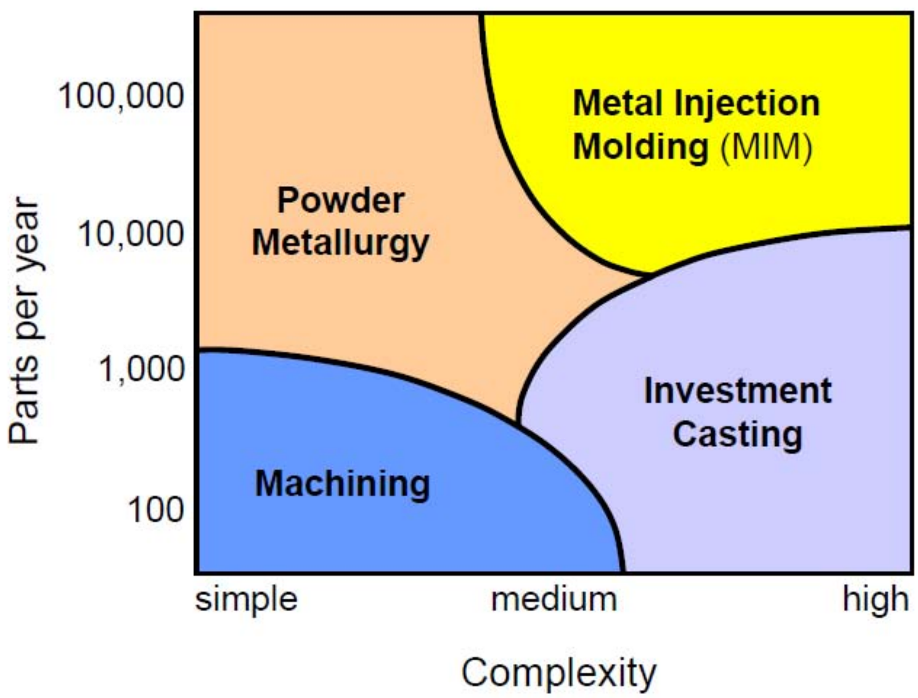
- little difference in hardness and bulk chemistry
- small difference in yield strength, tensile strength, and ductility
- potentially large differences in impact toughness, fracture toughness, corrosion resistance, and fatigue endurance strength.

Design Principles

Recognizing Good Candidate Parts

The strengths of MIM trace to production quantities, shape complexity, material performance, and component cost. MIM has a cost advantage in instances where the shape complexity is outside the comfort range of other manufacturing routes.

Small quantities, at a few thousand per year, give little opportunity to amortize tooling and engineering costs and are generally discouraged. Often the best match is with production quantities exceeding 200,000 per year, but a few projects are successful at 5,000 parts per year. On the other hand some components in cell telephones, computers, eyeglasses, and dental orthodontic brackets reach levels approaching 100 million per year.



Shape complexity is an area where MIM is strongest. It depends on the number of engineering specifications required to define the component. MIM is often applied for components ranging from 20 specifications (dimensions, locations, surface finish, and such) on the engineering definition to more than 250 specifications. Components with many features often require post-sintering machining operations to hold tolerances. About half of the production components have over 70 features. Components, such as wristwatch cases are good examples of the complexity level where MIM excels.

Material properties are a third selection factor. Many materials are available via MIM. When the material is difficult to machine, such as tool steels, titanium, ceramics, stainless steel, or nickel-base alloys, then MIM is most beneficial. Because of widespread use, stainless steels or oxide ceramics are usually good choices from a cost standpoint. The properties attained in MIM converge to those listed in engineering handbooks.

The key criteria that help identify good MIM candidates are summarized as follows:

- *production quantity more than 5,000 per year, often exceeding 200,000 per year*
- *number of engineering features up to 250, most often in the range of 75*
- *most materials are available, but stainless steels, oxide ceramics (alumina, zirconia), steels, tool steels, nickel alloys, iron-nickel soft magnetic alloys, and specialty alloys of tungsten, titanium, cobalt-chromium, and electronic alloys are most popular*
- *property levels generally rival handbook tabulations for similar compositions and heat treatments.*

Component Surface Finish

If a matte surface finish is acceptable, then MIM requires no secondary polishing after sintering. This is a significant cost benefit over other production technologies. Lustrous surface finishes are possible by polishing. The time required to achieve a high polish is shorter for MIM versus casting. Thus, high polish conditions are possible. The surface finish advantage with MIM is two-fold. First, the time is shortened by the small amount of material removed after sintering. But more significant, especially in areas of great aesthetic concern, jewelry, watches, computer logos, designer eyeglasses, and designer luggage, is the fact that no subsurface pores are exposed in MIM. This is not the case in casting, where larger residual pores can lie just below the surface and are opened in polishing, making the component useless.

Component Size Range

MIM is applied to smaller components, and half of all parts are smaller than 25 mm or 1 inch in maximum dimension. Much larger sizes exist, up to 10 inches or 250 mm, but most are smaller. A few large ceramic components are in production for specialized aerospace and liquid metal handling applications. But, MIM is most competitive for components shorter than about 125 mm (5 inch). On the other hand, MIM is widely used for small components, such as dental orthodontic brackets, where features are very small.

Most of the MIM components tend to be slender with thin walls. Thinner walls reduce mass and ensure rapid cooling and heating during molding. The most common wall thickness is about 3 mm (0.125 inch) or less. Further, MIM works best when the wall thickness is uniform to ensure rapid and uniform processing. It is thickness that determines mold cooling time and debinding time, so thick sections are avoided when possible. An especially difficult situation is when thick and thin sections join. The difference in cooling and heating rates generates stresses that damage the component. During debinding the thick section gives up binder first and is weak, while the thicker section induces a stress that can cause cracking. Thus, the typical ratio of maximum to minimum wall thickness is about 2 to 3. Other ranges are possible, but require special fixtures during processing to help avoid distortion.

Mass Range

Component mass in MIM tends to be typically in the 10 gram range (one-third ounce) About 10% of the MIM products are below 1 gram. These are mostly dental orthodontic brackets. At the other end of the design population are components with mass in the few hundred gram range, such as handgun bodies. Only about 10% of the MIM designs are more than 100 grams. Generally, the most popular industrial and medical designs are in the 8 to 16 gram range.

MIM Orthodontic Brackets weighing less than .25 grams

MIM Planetary Gear at 2.600 OD

MIM excels at forming smaller components where much mass removal would be required by machining.

Manufacturing Considerations

Mold Attributes and Limitations: The mold for MIM has a large influence on the product dimensional capability during production. Once the component is ejected from the tool there remains little capability to adjust dimensions except with extra cost. MIM tooling looks similar to that used in plastic injection molding, although molds are oversized to account for the large sintering shrinkage. In most instances, the tool set consists of one to four cavities serviced by tool pieces that move in coordination with the opening, molding, and closing actions; such as ejector pins.

Typical Smith mold with Hot Sprue Bushing.

Tool design and process design go hand in hand. Mold design and mold fabrication are treated in detail in plastics molding handbooks. In MIM there are additional concerns with the higher thermal conductivity and density of the feedstock. Metal particles make the binder much more thermally conductive when compared to plastics. Likewise, the metal particles increase the feedstock density significantly over typical plastics. Otherwise, MIM relies on principles found in plastic molding.

Parting Line

An extreme situation occurs with feedstock intrusion along the parting line to give flashing.

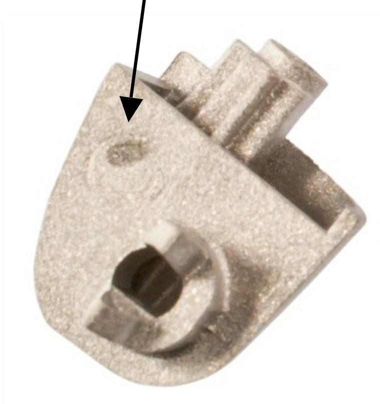
The parting line location is one important decision in MIM tool design. The parting line is the trace left on the molded component surface where the mold sections meet. Cosmetic and functional requirements may help guide parting line location.

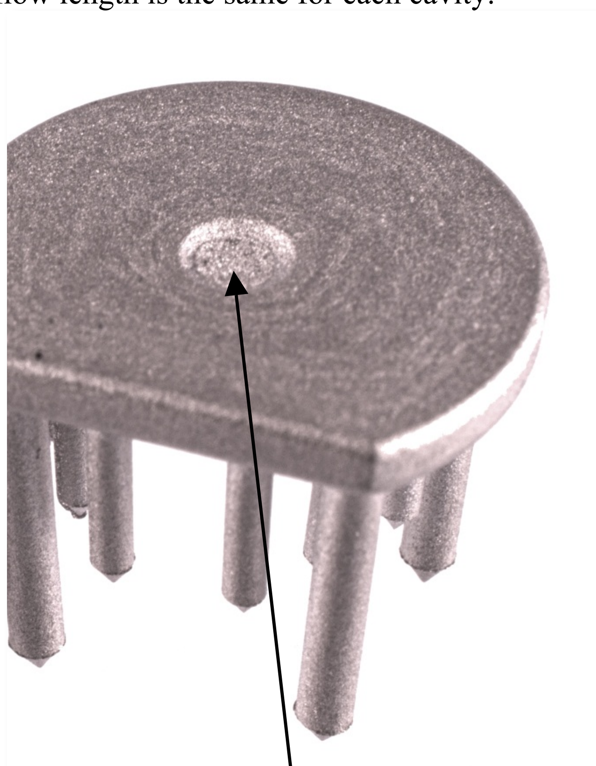
Sprue, Runner, and Gate

The flow path into the mold cavity consists of a sprue, runner, and gate. The sprue connects the molding machine nozzle to the mold to deliver molten feedstock into the cavity. In many MIM operations sprues are tapered with a typical diameter near 6 mm and 5 degree taper. When the mold opens for ejection, the sprue is pulled and recycled. For faster production and the minimization of regrind, the sprue and/or runner are kept hot to avoid reheating and recycling this portion of the feedstock. This option is called a hot runner system or hot sprue.

From the molding nozzle the sprue leads into the runner, which then directs the melt into the mold cavity through the gate. Small runners allow for slow filling, so a large runner is desirable, with a typical diameter from 3 to 6 mm. Of course a large runner means relatively less of the shot goes into the part cavity. A circular runner design is desirable since this reduces friction and heat loss during filling, but other designs are less expensive to construct. Multiple cavity molds require balanced designs so the feedstock flow length is the same for each cavity.

Gate Mark on non-critical to function and hidden surface





Gate mark placed in recessed pocket

At the end of the runner is the gate leading into the mold cavity. The gate leaves a surface blemish on the part. It is small and designed to freeze before the part, runner, or sprue freeze. This keeps the cavity packed to avoid sink marks (recessed surfaces) during cooling. Excessive pressure on gate freezing causes sticking in the mold. It is desirable to have the gate located on the thick portion of the component. This reduces heat loss and premature freezing and lowers the pressure required for mold filling.

Gate size is determined by filling speed and component thickness and is an area of expertise for MIM tool designers. Usually the gate is smaller than the component wall thickness. But too small a gate can introduce defects, tool wear, and incomplete filling. Small gates also contribute to powder-binder separation, which is a cosmetic defect.

Gate placement considers how to minimize weld lines. Weld lines form when the feedstock splits and then rejoins after flow around posts or other features. If the molding conditions are such that the feedstock is warm, then the weld line heals. Alternatively, if the feedstock cools, then a weld line defect forms. Computer simulations (mold flow analysis) help avoid these difficulties by suggesting either different molding parameters or different gate locations.

Venting

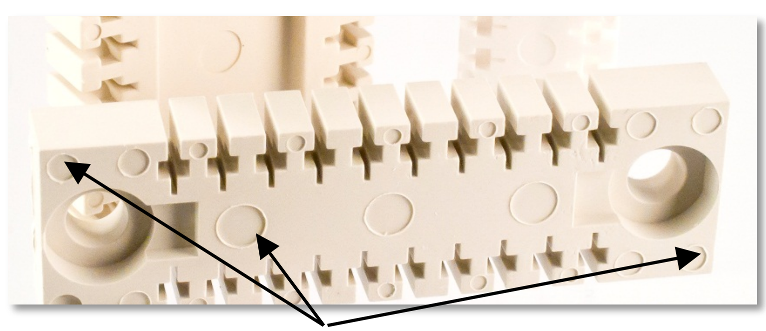
The mold cavity is full of air when the cycle starts. During the injection cycle this air is pressurized by the incoming hot feedstock and forced out of the cavities through vents. Venting is needed in the last portion of the cavity to be filled (opposite the gate). Vents are very thin reliefs typically 0.015 mm (0.0006 inch) deep, and up to 12 mm (0.5 inch) wide for large MIM parts. Ideally, venting leaves no observable trace on the part surface.

Venting is also necessary to allow the part to be ejected from the tooling. For example, a shape with a closed end cannot be ejected without creating a vacuum; otherwise an additional ejector pin must be built into the forming tool which is pulled first to vent the mold.

Ejection

Once the molded part has cooled it must be ejected. The ejection force depends on the contact area between the tooling and component, tool surface finish, coefficient of friction, and thermal contraction on cooling. Adhesive phases in the binder can cause sticking. A slight taper (or draft) in the tooling greatly aids in reducing ejection force; often just 0.5E is sufficient. Corners in the cavity are usually rounded for easier ejection; a radius of 0.2 mm (0.008 inch) is satisfactory, but they can be as tight as 0.05 mm (0.002 inch).

To eject the part, ejector pins push the part out of the cavity. Inserts, internal cores, threads, or any type of under-cut (trapped steel coring) must be retracted first to allow free ejection. Ejector pins leave witness lines on the component, since they concentrate the ejection force on a soft and often still warm molded shape. Larger pins are desirable to reduce the stress. The location and number of ejection pins depend on the component size, binder strength, and tooling complexity. Normally, the pins are placed to impress on noncritical locations and constitute more than 10% of the projected compact area.



Ejector Pin Marks on Ceramic Components

Tool Motions

Molding starts with the closure of the mold cavity. The molding machine nozzle is inserted into the sprue bushing. After contact, a premeasured quantity of molten feedstock is forced into the cavity. Pressure is sustained on the cooling feedstock until the gate freezes, and after complete cooling the component is ejected. Between the time when the gate freezes and the part is ejected while it is still cooling, the screw is turning to plasticate and meter the next shot of hot feedstock.

The pressure in the molding cavity increases rapidly as the molten feedstock enters the cavity and that pressure is held until the gate freezes. Once the gate has frozen the molding machine no longer controls the cavity pressure. Cavity pressure determines the final part mass and dimensions. A shot-to-shot mass variation is a means to monitor the success of proper control.

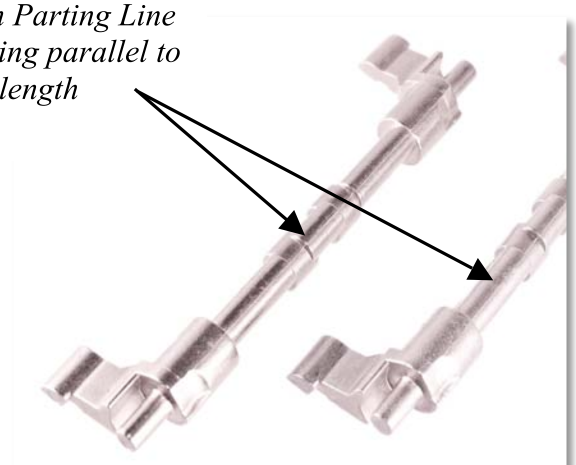
After mold filling, as the feedstock cools, a natural pressure reduction occurs due to binder thermal contraction. At the point of ejection the residual pressure in the cavity should be very low. Otherwise, the component will stick in the mold cavity. For ejection, pins move from flush positions on the tool walls and push the component from the cavity.

Robot coordination is an important aspect of automation. Modern molding machines integrate the robot control and coordination with the molding cycle. Further, simple tests such as mass or size determination are possible after molding to ensure proper quality.

Blemishes from Tooling

A successful MIM part design allows for locating the parting line, ejector pin marks, witness lines, and gate in non-critical areas. Often the gate is located on a parting line, so these two blemishes go hand-in-hand. Parting lines can be placed along component edges to reduce visibility. Sometimes features within the mold set are inserted to allow changes, replacement, inter-change-ability, and servicing. These inserted components will leave witness lines where they blend into the parent part surface.

Main Parting Line running parallel to part length



Early in the design process, the designer needs to consider placement of these blemishes in areas where they will not detract from the operation or aesthetics. Alternatively, the gate can be removed by grinding or polishing after molding, but prior to debinding and sintering, since the material is easily removed then.

Dimensional Tolerances

Metal powder injection molding is a hybrid between plastic molding and sintered powder metallurgy. The tolerance capabilities are also a hybrid. Plastic molding generally has a tolerance range from ±0.05 to ±0.5 mm (±0.002 to ±0.020 inch). Sintered powder metallurgy technologies generally have a tolerance range from ±0.1 to ±0.3 mm (±0.004 to ±0.012 inch), and sintered ceramics are much larger. MIM is limited by its ingredients - plastics and sintered materials - to a general tolerance range centered on ±0.1 mm (±0.004 inch) or slightly better with special efforts.

There are two issues. The first is the location of the mean size for the specified feature - accuracy. The second issue is the variation about the mean - precision. The further the mean is from the target size, the smaller the allowed variation or tolerance zone. Adjustments to the mean size are easier to accommodate in MIM than adjustments to the variability. For example, changes in molding conditions, solids loading, sintering temperature, or sintering time can be used to relocate the mean size of the product.

MIM component production ranges over a large size range, making it difficult to address tolerances directly over such a wide range. In some instances, the choice has been to create a table of tolerance versus size, showing capabilities as follows: These tolerances can be obtained within a single batch but wider variation is usually observed over time.

- *± 0.05 mm (0.002 inch) for features below 3 mm (0.12 inch)*
- *± 0.08 mm (0.003 inch) for features between 6 and 15 mm (0.25 to 0.6 inch)*
- *± 0.25 mm (0.01 inch) for features between 30 and 60 mm (1.2 to 2.4 inch).*

The coefficient of variation is used to normalize dimensional variability. Statistically the coefficient of variation C_V is defined as the standard deviation divided by the mean dimension, often given as a percentage.

For the more typical size range encountered in MIM production, near 25 mm (1 inch), the general industry capability is ± 75 μm (0.003 inch), or a coefficient of variation ± 0.3%. This is generally reflective of the technology once the production process is tuned to center the dimensional variation on the desired mean size.

In large volume production operations tool wear becomes an issue. To avoid the expense of mold replacement or refurbishment, the desire is to have a wider tolerance band to allow for tool wear, say ± 0.5%. This ensures a high process yield of acceptable parts over a longer time. Many industrial firms quote process capabilities based on at least six standard deviations (the mean plus and minus three standard deviations, which includes 99.74% of the product).

In production, the sources of variation are -

- ***feedstock*** *- mixture inhomogeneities and lot-to-lot feedstock variations*
- ***molding*** *- inherent process variation shot-to-shot associated with the molding machine and its sophistication as evident by the integrated controls*
- ***cavity*** *- largely from variations between tool cavities, systematic filling differences, and cavity wear over time*
- ***furnace*** *- associated with furnace-to-furnace differences in debinding and sintering*
- ***placement -*** *variation due to location differences within the thermal processing equipment*
- ***day -*** *normal daily fluctuations, including operator, humidity, handling, tool wear*
- ***vendor -*** *vendor-to-vendor differences.*

Audits on these factors show vendor differences are the largest. One consequence is that molds often cannot be transferred between vendors with success. The next largest factor is feedstock variation. Although the sintering furnace is often blamed for dimensional variations, in reality sintering simply amplifies earlier defects. Sintering transforms subtle molding variations into dimensional scatter. In repeated statistical surveys, molding accounts for 60 to 80% of the MIM dimensional variation, most of which becomes evident after sintering.

The following table summarizes the situation based on both the typical coefficient of variation and the best possible in the industry (without secondary operations).

A factor in determining dimensional tolerances is surface roughness. Nominally the tolerance specification cannot be any tighter than ten-fold the surface roughness. Most MIM operations deliver an average surface roughness near 1 µm. On this basis surface roughness limits the tolerances to probably ±10 µm at best for MIM.

An option for tighter tolerances is to machine critical surfaces after sintering. Post-sintering machining is often used in MIM, ensuring precise final dimensions, but in some cases it adds considerably to the fabrication expense.

Process Variations Observed in MIM Component Production

(actual values depend on many site-specific and component-specific factors)

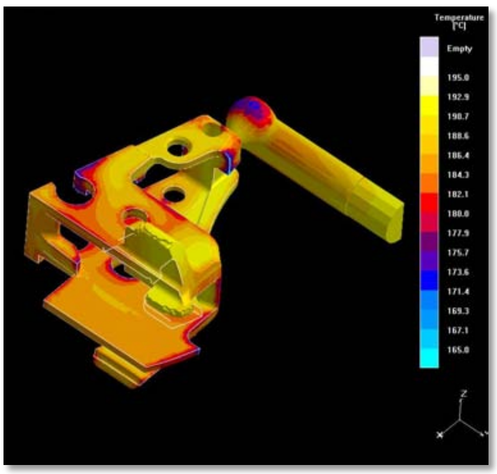
feature	**best possible ±**	**nominal or typical ±**
absolute dimension	0.025 mm (0.001 inch)	0.05 mm (0.002 inch)
Angle	0.05°	2°
density	0.2%	1%
dimension	0.05%	0.3%
flatness	0.1%	0.2%
hole diameter	0.04%	0.1%
hole location	0.1%	0.3%
parallelism	0.2%	0.3%
perpendicularity	0.1% or 0.1°	0.2% or 0.3°
roundness	0.3%	0.3%
surface roughness	0.2 µm (8 µ inch)	0.8 µm (32 µ inch)
weight	0.1%	0.4%
corner radius	0.5 mm (0.02 inch)	0.3 mm (0.012 inch)

The fabrication of sharp corners and small features is limited by the particle size. Indeed, if the particles are large compared to the feature, then the particles simply will not fill out the feature. As a rule of thumb, no feature should be specified to a size that is not at least ten-fold larger than the particle size. For a sharp corner fabricated from 10 µm powder this would say that the corner radius should be 100 µm or larger (0.1 mm or 0.004 inch). Attempts to form sharp edges on cutting tools, knives, or scissors using MIM have been unsuccessful since the particle size limits the sintered edge retention.

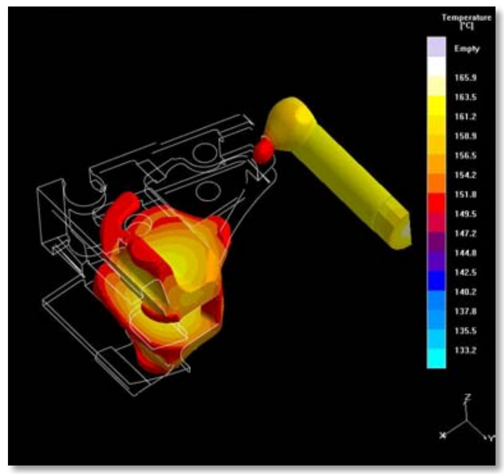
Computer Simulation for Defect Avoidance

The success of MIM is linked to its ability to generate precise, complex shapes at the molding machine and then to sinter that shape to the target size and specifications. This requires quality tooling and excellent process control. Computer software is used to simulate molding, tool design, debinding, and sintering. Several simulations are available.

The computer programs emphasize a combination of mold filling, packing, and cooling simulations. Such packages allow process evaluation prior to commitment to tooling or manufacturing equipment. Cost evaluations are possible based on differences in raw materials, the number of tool cavities, and options on processing cycles.



Cooling Simulation



Short Shot Simulation

Often subtle variations exist in sintering shrinkage that need to be predicted to minimize tool construction errors. For example, nonuniform density in molding leads to distortion in sintering. Further, subtle factors such as gravitational forces in sintering and polymer orientation in molding cause subtle anisotropic shrinkages that contribute to dimensional variations. The desire is to have computer software incorporate these factors into the tool design to help place runners, gates, vents, and cooling paths. Once the shape and gradients, or stresses, are known in the molded body, then finite element computer simulation tools allow prediction of final sintered size and shape.

These simulations require a database of material properties, component specific details, and process details. Unfortunately, many of the modeling parameters are not known with precision and are estimated. For well-controlled operations, computer-assisted design is an inexpensive way to explore options before mold production.

Material Properties

Contrast and Comparison on Properties

In most cases MIM products are fairly close to the strength and hardness of their wrought counterparts, and in some cases are even stronger. The composition, density, elastic modulus, and similar attributes are pretty much as found via other manufacturing routes. For example, the tensile properties of wrought and MIM Inconel 718 superalloy compare as follows:

wrought typical yield strength = 760 MPa (110 ksi)

MIM typical yield strength = 1055 MPa (153 ksi)

Likewise the MIM ultimate tensile strength and elongation to fracture were attractive when compared to wrought materials. Indeed, the MIM elongation was nearly 6-fold the specified minimum for wrought material. In other property comparisons, such as magnetic, optical, corrosion, biocompatibility, elastic, or inertial properties, a similar observation holds – MIM products are essentially equivalent to handbook compilations. There are a few exceptions in fracture toughness, so for situations where impact or crack propagation are a concern it is advised appropriate testing be conducted.

Typical MIM Properties

Tensile properties of MIM products are extremely well documented. Typical room temperature tensile properties for the common compositions are compiled below and a second table shows the typical strength of some ceramic products. Ductile alloys are characterized by yield strength, ultimate tensile strength, fracture elongation, and hardness (given as Vickers hardness number VHN, Rockwell B or C HRB or HRC). Generally the densities are close to those reported in standard handbooks. Heat treatments provide a means to adjust the properties and hot isostatic pressing is occasionally used to reach full density as noted by HT or HIP in the table. Considerable variation is possible in these cycles, so only one example is listed, typically the cycle giving the highest hardness. Not all suppliers support all of these materials but the array of MIM materials and properties are quite broad.

Tensile Properties of MIM Alloys

(HT = heat treated, HIP = hot isostatically pressed)

material (designation)	density %	yield strength MPa	tensile strength MPa	fracture elongation %	hardness
cobalt-chromium F75	99	550	880	4	25 HRC
cobalt-chromium F75 (HIP)	100	560	1010	30	25 HRC
Copper	93	30	145	23	43 VHN

material (designation)	density %	yield strength MPa	tensile strength MPa	fracture elongation %	hardness
Hastelloy X (HT)	98	303	675	74	30 HRC
Inconel 718 (HIP, HT)	100	1055	1380	29	42 HRC
Invar Fe-36Ni	98	240	425	40	65 HRB
iron	96	100	230	40	65 VHN
iron-molybdenum Fe-5Mo	98	210	410	34	66 HRB
iron-nickel Fe-2Ni	96	190	345	30	55 HRB
iron-nickel Fe-8Ni	95	310	430	21	80 HRB
iron-nickel Fe-42Ni	99	250	490	43	59 HRB
Kovar (F15)	98	300	460	25	65 HRB
stainless 17-4 PH	96	750	900	10	25 HRC
stainless 17-4 PH (HT)	96	1090	1185	6	35 HRC
stainless 17-4 PH (HIP)	100	1103	1137	13	38 HRC
stainless 304L	97	240	480	35	85 HRB
stainless 316L	96	175	520	50	67 HRB
stainless 318	97	230	590	29	89 HRB
stainless 410 (HT)	95	1240	1520	5	40 HRC
stainless 440C	96	410	620	2	43 HRC
stainless 440C (HT)	98	1560	1600	<1	58 HRC
stainless PANACEA	99	670	960	35	25 HRC
steel 1020	96	185	380	23	67 HRB
steel 1060	97	260	580	25	80 HRB
steel 2200	96	125	290	40	45 HRB
steel 2700	95	225	415	26	69 HRB
steel 4140	97	390	580	15	18 HRC
steel 4140 (HT)	93	1240	1650	2	46 HRC
steel 4340	96	480	620	6	20 HRC

material (designation)	density %	yield strength MPa	tensile strength MPa	fracture elongation %	hardness
steel 4340 (HT)	96	1400	1600	2	48 HRC
steel 4605 (HT)	96	1480	1655	2	48 HRC
steel 4640 (HT)	97	1400	2000	3	30 HRC
titanium	98	500	620	22	95 HRB
titanium (HIP)	100	700	800	25	195 VHN
titanium -6-4	98	800	900	17	35 HRC
tool steel M2 (HT)	99	1000	1100	1	62 HRC
tungsten-copper W-10Cu	98	530	540	1	280 VHN
tungsten alloy W-5Ni-2Cu	98	900	1050	10	35 HRC

Rupture Strength of Injection Molded Ceramics

(compositions in wt.%)

material	density %	strength MPa	Weibull modulus	hardness VHN
99% alumina (Al_2O_3)	98	300 - 450	9	1200 - 2000
alumina-zirconia (Al_2O_3-$20ZrO_2$)	97	400 - 600	---	1800
cemented carbide (WC-10Co)	100	1500 - 2600	12	1300 - 1700
cemented carbide (WC-7Co-1TaC)	100	2100 - 2200	---	1700
silicon nitride (Si_3N_4-$8Y_2O_3$)	98	350 - 800	15 - 35	1600
zirconia (ZrO_2 -$3Y_2O_3$)	95	200 - 800	12	1200

For MIM systems the strength measured over repeat samples typically has a standard deviation of less than ± 20 MPa (± 3 ksi) and the elongation has a standard deviation of approximately ± 1%. When different operations are compared, most properties are similar, but a few, such as impact toughness, vary considerably.

Testing Standards

Industry standards for MIM have been formed by the regional trade associations such as the European Powder Metallurgy Association (Shrewsbury, UK) and Metal Powder Industries Federation (Princeton, NJ). The standards cover testing procedures for the powders and sintered materials, composition ranges for popular materials, and property levels for sintered materials.

With respect to mechanical properties, several test bar geometries are used in MIM. Flat tensile bars are easily formed by MIM using low cost tooling. After sintering, depending on the initial solids loading and sintering shrinkage, the thickness ranges from approximately 4 to 6 mm cross-section and 20 to 30 mm gauge length is common (about 0.25 inch thick and 1 inch gauge). It is often molded in a cluster with other test samples, such as a transverse rupture bar or impact bar or corrosion test coupon, also useful for hardness tests.

Sintered test bar (top)
Green test bar (bottom)

Another tensile test sample option is a round bar 38 to 90 mm (1.5 to 3.6 inch) long with a typical diameter between 4 to 5 mm (0.16 to 0.2 inch), shown in Figure 5.29 as it is being extracted from the molding machine. A hybrid tensile bar design is flat but rounded, but it has a tendency to give premature fracture out of the gauge length.

Impact bars range from square cross-sections 10 mm by 10 mm by 55 mm length (0.4 by 0.4 by 2.2 inch) to subsize samples of one-half or one-fourth the cross-sectional area. In some cases the samples lack the standard 2 mm deep 45E notch. So several variants are in use. Because of sensitivity to the test sample, users should decide if impact testing is needed and elect a geometry relevant to their application.

Other property tests are covered by standard industry tests, including magnetic properties. Here the convention is to use a 25 oersted maximum applied field. Other data might include surface finish, microstructure, grain size, porosity, hardness, wear resistance, corrosion resistance, chemical composition, and various other parameters.

Corrosion testing can be simple using immersion tests. One corrosion test applied to MIM stainless steels is to immerse a sample 5 by 10 by 55 mm (0.4 by 0.4 by 2.2 inch) in a 2% sulfuric acid solution at room temperature for 1,000 h. However, it is faster to rely on a 6 min immersion in a copper sulfate solution and to inspect for copper plating or other attack (ASTM F 1089). Other tests for corrosion include boiling water immersion for 30 to 180 min (ASTM F 1089). One effective test, commonly used but not standardized, is to immerse the sintered component in chlorine bleach and observe for discoloration over one minute.

Costs

Typical Project Costs: Cost analysis is an important aspect of engineering design. One approach is to send out a component design and solicit responses from vendors. That usually results in a large variation in estimated cost estimates.

In MIM, the approach to estimate component cost is to sum the costs accumulated at each manufacturing step, starting with tool fabrication and extending to secondary operations and final inspection. The increments are as follows:

- tool cost
- feedstock cost (powder, binder, mixing or purchased feedstock)
- unit fabrication costs (mixing, molding, debinding, sintering)
- secondary, finishing, inspection, and packaging costs
- facility overhead burden
- profit, tax, interest, and risk aversion.

Costs depend on design factors such as part complexity, material selection, and component size. The estimation procedures for tool cost are well established in plastic injection molding, providing a sound basis for MIM. Indeed some tool vendors have on-line tool cost estimators.

Raw material cost is dominated by the alloy. Polymers used as binders tend to be a low cost factor and final price is nearly insensitive to the polymer formulation. Unit costs in molding, debinding, and sintering depend on the facility and installed equipment; generally these costs are based on an hourly rate, so less cost is accumulated if each step is performed quickly, an advantage to small and thin shapes.

The secondary operations are often performed by outside vendors, and MIM has no advantage in this regard.

For the core manufacturing steps, unit operation calculations are developed for each step to accumulate a total fabrication cost. Although there are recognized differences in all cost factors, including labor, interestingly labor is not a dominant factor; MIM succeeds in both expensive and low labor cost regions.

Tooling Cost

Tool cost for MIM is based on principles encountered in plastic injection molding. Although many models exist, the most accurate approach assumes purchase of a standard mold base. It then calculates the time needed to machine the component features into a cavity. For multiple cavities, the machining time for the first cavity is used to estimate the time and cost for each additional cavity, recognizing some cost reductions with increased experience. Mold cost is calculated from the total construction time multiplied by a shop hourly rate, with additions for profit and administrative costs.

Detailed quantitative cost analysis of tool cost builds from the assumption that a standard mold base is purchased and converted into the customized design required for the component molding. It needs to be modified to include the specific cavity and related sprue, runner, and cooling channel. Major cost additions are associated with hot runner systems.

Tooling tolerances are more stringent than part tolerances, and in many estimates the tool tolerance is held to less than 20% of the component allowance. Accordingly, considerable time is used to fabricate a precise tool for a tightly toleranced component, especially when the number of features is large.

The specified tool surface finish incurs a cost, especially if a polished tool is required. In a similar manner, texturing, lettering, or insignias on the tooling add to the tool fabrication time and cost. The tooling cost depends on several factors. MIM tool costs ranged from a low of $2,500 to $125,000 or more.

Tool Life

Because tooling and engineering are large initial costs, extension of mold life is important to the economics of MIM. As a generalization, MIM is not cost effective in hard tooling for production quantities below 5,000 parts per year. Using soft tooling on the other hand, some ceramic and cemented carbide components are produced in lots as small as 200.

Most MIM shops operate for about 100,000 shots without tool maintenance. Several coating technologies extend tool life, especially in resisting wear from harder and more abrasive particles. The coatings include intermetallic compounds, boride layers, hard nickel-phosphorus electroplates with embedded Teflon particles, hard sputter coatings, and various spray, vapor, or reaction interfaces. Although they all add expense to tool creation, there are possible gains over time for larger production quantities.

Tool Warranties: Some tool shop offer warranties for their molds. Typically this is done by increasing the part price to accumulate money to repair or replace components that will wear at some point. Smith may do this upon request, but we believe the lowest over-all cost is to pay these costs as they are actually needed.

Component Costing

The cost for producing a MIM component is depends on the material and several other variables, including the production quantity, equipment, technology, and labor rates. Component costing usually starts with the raw material cost, and popular stainless steel alloys are very favorable in this regard. After that the time in each manufacturing step is critical, since cost accumulates based on time. This makes MIM most attractive for thinner walled structures that can pass through production quickly.

Across the MIM industry there is considerable variation in costs, markets, and production approaches. However, surveys show that most of the successes are priced near $1 per part, but range from a low of $0.05 to $400 per part. Surveys show the typical MIM component sells for about $133 per kg. However, smaller 0.1 g components are valued closer to $600 per kg.

Competitive Forces

A wide variety of forming routes are available for metals. Thus, competing technologies greatly influence the viability of MIM. Users say that the decision to use MIM over competing technologies usually starts with cost, but includes issues of shape capabilities, productivity, surface finish, and precision. The cost advantage for MIM, versus other forming techniques, increases when it eliminates machining, grinding, or other finishing steps, especially for small components. For large, simple shapes, MIM proves unattractive.

A Comparison of MIM with Other Technologies

attribute	MIM	powder metallurgy	casting	machining
density of theoretical	98%	85%	95 to 99%	100%
relative strength	100%	50%	98%	100%
magnetic response	100%	70%	95%	98%
surface finish	0.4 to 0.8 μm	2 μm	3 μm	0.2 to 2 μm
wall thickness	10 to 0.1 mm	2 mm	5 mm	2 mm
complexity	high	low	medium	high
design flexibility	high	medium	medium	low
production rate	high volume	high volume	low volume	low volume
material range	high	medium	medium	medium
mass range	0.003 g to 1 kg	0.1 g to 10 kg	1 g up	0.1 g up

Each technology is best suited to a particular combination of materials, tolerances, sizes, shapes, and properties. For example, casting techniques excel in shape complexity, but lack in surface finish and dimensional precision. At high production quantities, machining techniques suffer from material waste and production costs. Cost is usually the critical parameter in selecting a net-shaping technology.

Market Considerations

MIM operates in the context of sintered materials technologies. Globally sintered materials contribute near $100 billion per year to the economy. About 25% of that global activity is in North America. The production of metal powders alone in North America is annually valued at $4 billion. Sintered carbide and metal parts production in North America is valued near $8 billion, where metal-bonded diamond cutting tools, sintered magnets, and semi-metal products contribute significantly to industry heavily focused on automotive and consumer products.

Powder metallurgy consists of about 4700 production sites around the world involved in variants of the technology. Most popular is the PM press-sinter variant that relies on hard tooling, uniaxial compaction, and sintering. Based on tonnage, about 70% of the press-sinter products are for the automotive industry. However, on a value basis the story is dramatically different; metal cutting and refractory metal industries generate the largest value. Here the products include tantalum capacitors, tungsten light bulb filaments, tungsten carbide metal cutting inserts, diamond coated oil and gas well drilling tips, high performance tool steels, and molybdenum diode heat sinks. Compared to the other powder technologies, the MIM variant is still relatively new and small, but it is growing at 14% per year. In 2011 MIM products were globally valued at approximately $1 billion. This sales activity is spread over about 300 to 400 firms (some are divisions of the same company, simply different production sites).

History of Success

MIM followed behind the first developments in plastic injection molding. Early polymers were thermosetting compounds; Bakelite, the first manmade polymer, was invented about 1909. Subsequently, as thermoplastic such as polyethylene and polypropylene emerged, forming machines appeared to facilitate the shaping of these polymers a few years later. The first demonstrations of MIM were coincidental with the emergence of plastic injection molding, starting in the 1940s and reaching commercial status in the 1970s.

Major attention came when a California MIM firm won design awards for a screw seal used on a Boeing jetliner and a rocket thrust-chamber for Rocketdyne and the US Air Force in 1979. Soon several patents emerged. By the middle 1980's the technology landscape showed multiple actors.

By the early 1990s, the technology had spread around the world for small, complex, and high value components ranging from automotive fuel injectors to watch cases. Today, about 400 sites practice the technology, about 20 to 25% for internal products (such as firearm, watch, dental, or medical components) and the vast majority are able to form custom devices for designers, such as Apple, Motorola, Dell, HP, Honda, BMW, Samsung, Sears, Toyota, Chrysler, Seagate, Glock, and GE.

Industry Structure

The MIM industry structure and interactions shows generally the firms fall into a few key focal points. Everything revolves around the fabricators, firms that form components to satisfy the specifications of the users. Conferences on MIM started in 1990 and continue today, where participants gather to share information on technology advances. At these conferences the actors in the industry generally come from one of the following sectors:

- **ingredient suppliers** – polymers and powders, approximately 40 firms that provide most of the MIM powders, although about 400 firms supply metal powders of various chemistries, particle sizes, particle shapes, and purities
- **feedstock production** - formulate powder-binder mixtures for sales to molding firms; globally there are usually about 12 feedstock suppliers
- **molding firms** - both custom and captive molders; 83% of all parts production is categorized as custom manufacturing
- **thermal processing** - firms that own debinding and sintering equipment that provide toll services; about six firms are active in this area; a few firms provide toll hot isostatic pressing to force 100% density when required in medical or aerospace fields
- **designers** - systems design firms associated with large multinational uses that intersect with the MIM industry, a few independent designers are available to handle projects
- **equipment suppliers** - firms that design and fabricate furnaces, molders, mixers, debinding systems, robotic systems, and other devices such as testing or assembly devices
- **consumables** - suppliers of process atmospheres, chemicals, molds, polishing compounds, machining inserts, packaging materials, heating elements, and sintering substrates
- **adjuncts** - including researchers, consultants, design advisors, business agents, lawyers, conference organizers, magazine editors, and patent attorneys.

Component production is the central activity. It is split between internal and external products, referred to as captive and custom molders. Likewise it is supported by two parallel supply routes, depending on the decision to self-mix or to purchase premixed feedstock. An example captive molder would be a firearm company that uses MIM to fabricate some of the safety, trigger, or sight components. On the other hand, custom molders also can make these same components, but just as well can be involved in several application areas as determined by their customer base.

As outsourcing increases for multinational firms, custom fabrication is growing. In recent years growth in MIM has come with the shift to custom molding which services a wide variety of applications. The custom molding firms have joined together in efforts to advance the industry, via collaborative marketing efforts, promotion of material standards, publicity via annual awards, and sharing of business data. Although declining, captive molding still remains an important part of the MIM industry. Although the sales growth varies year to year, in recent times the global sales gain has sustained at 14% per year.

Statistical Highlights

Measures of the MIM growth are possible through several parameters, including the following:

- **Patents** - Since the start of MIM the total patent generation is large, exceeding 300 by year 2000, but in more recent years the rate of patent generation has slowed and there are today about 200 currently active patents.
- **Powder Sales** - In 2011 more than 9,000 tons of metal powder were consumed globally by MIM, with a growth rate in powder tonnage use approaching about 20% per year, but due to price reduction the value increases about 14% per year.
- **Feedstock Purchase** - The two options of self-mixing or purchasing feedstock seem to be of equal merit. Several older firms mix their own feedstock, but purchased feedstock is neither an advantage nor disadvantage; self-mixing does provide greater manufacturing flexibility.
- **Continuous Furnaces** - In 2011 the installed capacity of high volume continuous sintering furnaces reached 4,500 tons of products per year, or roughly half the industry production.
- **Component Size** - The most typical MIM part mass is in the 6 to 10 gram range. The mass range is from below 0.02 g to over 300 g, but the mean is under 10 g. The largest MIM parts are heat dissipaters for the control systems in hybrid electric vehicles at 1.3 kg and some aerospace superalloy bodies that have similar mass and dimensions reach 200 mm. A growing aspect of MIM is the microminiature components where features are in the micrometer range and this approached $68 million per year in sales for 2010.

Of the nearly 400 sites that currently practice MIM; the majority is located in Asia. The leading countries in terms of PIM were the USA with 106 operations, China with 69, Germany with 41, Japan with 38, Taiwan with 17, Korea with 14, and Switzerland with 12. The number of operations is not necessarily indicative of financial size, since one of the largest MIM facilities is in India, a country which only has 5 MIM operations, while the USA has the most firms.

Powder injection molding includes metals, ceramics, and carbides. Together these materials amount to sales for 2011 that reached $1.2 billion, with about $1 billion in MIM.

Summary for Global Powder Injection Molding Sales

total PIM sales 2011	$1.2 billion
total MIM sales 2011	$1.0 billion
total number of firms	400
total employment	9000
typical R&D staff	2
percent of firms self-mixing	72
total installed number of mixers	380
total installed number of molding machines	2000
total installed number of furnaces	900
percent of industry using thermal debinding	49
percent of industry using solvent debinding	26
percent of industry using catalytic debinding	14
percent of industry using other debinding	11
median part size, g	6

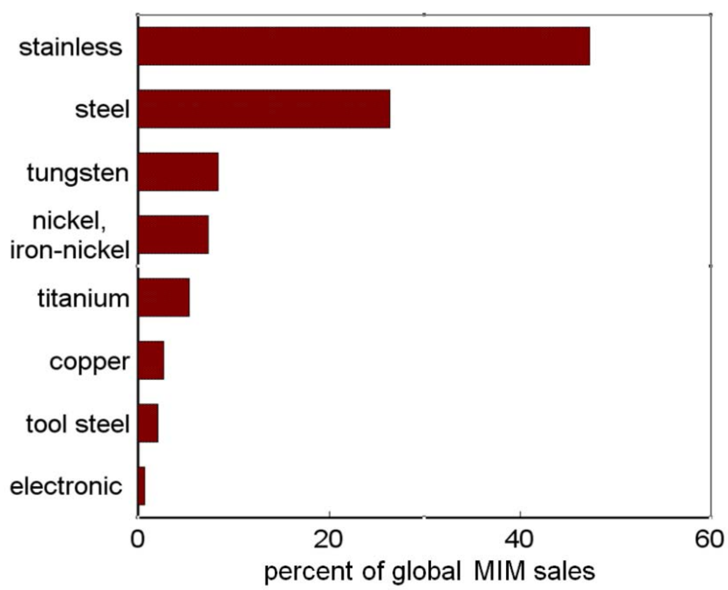
Industry Growth

Trends in MIM are evident by comparing year 2000 with year 2010. In early years MIM sustained compound annual sales growth at 22% per year with a 34% per year increase in the number of operations. In recent years the growth rates have been more modest with an overall average of 14% per year. Changes from year 2000 to year 2010 for MIM:

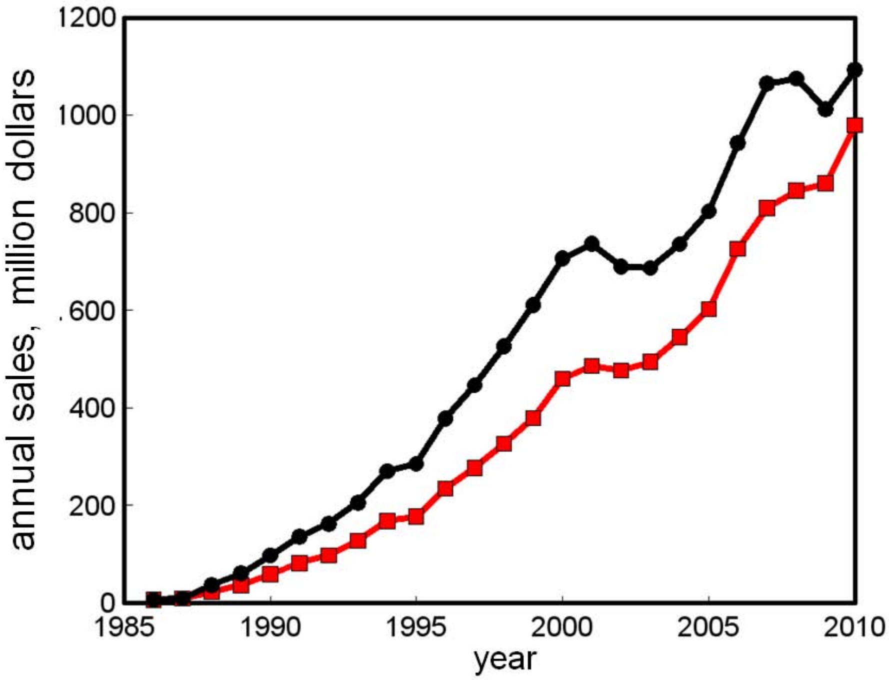
- number of MIM operations decreased 34%
- global sales increased 100%
- employment increased 100%
- installed molding capacity increased 79%
- installed sintering capacity increased 86%.

Sales Situation

Most of the common engineering materials are available in MIM, but material sales are as follows - 53% stainless steels, 27% steels, 10% tungsten alloys, 7% iron-nickel alloys (mostly magnetic alloys), 4% titanium alloys, 3% copper, 3% cobalt-chromium, 2% tool steels, 2% nickel superalloys, and 1% electronic alloys. On a tonnage basis the stainless steel portion of powder consumption is larger, reaching upwards to 60-65% of powder consumption, and because of that large consumption the powder price is lower, further fueling the use of stainless steel in MIM. Some of the powders are high priced, such as titanium, so the sales partition based on tonnage versus dollars is skewed due to a wide range in material costs.



MIM production for 2010 was in the neighborhood of $1 billion dollars (independent estimates were in the $955 to $984 million range). The recorded historical sales growth is plotted for PIM (black line - includes metals, ceramics, and carbides) and MIM (red) below.



Market Statistics

The largest market for MIM has historically been industrial components, including pump housings, solenoids, and handles, plumbing fixtures, and fittings. This amounts to 20% of global sales (more in Japan and less in Europe). Automotive components are the second largest market for MIM at 14% of global value (much higher in Europe and lower in North America). Consumer products are third largest market at 11% of the MIM sales, and these are dominated by Asia (cell phone, consumer, and computer parts). Next are the dental, medical, electronic, and firearm applications, each at 7 to 9% of the global MIM product value, with North America being the largest producer. Other contributions come from computer, hand tool, luggage trimmings, cosmetic cases, robots, sporting devices, and watch components.

MIM Applications

Markets for MIM are broad, and have grown from dental, medical, and firearm applications to include automotive, industrial, sporting, jewelry, hand tools, aerospace, computer, cell phone, and others. Consumer products include watches, latches, eyeglass hinges, and luggage clasps.

This tabulation shows that industrial components (valves, fittings, connectors) are the broadest market focus, followed by consumer (kitchen tools, toothbrush parts, scissors), and electronic components (heat sinks, hermetic packages, connectors). Automotive and medical are fast growing areas, especially in North America.

Consumer, cell phone, and computer uses continue to grow. Firearms went through a rapid escalation in recent years and essentially all of the firms are now using MIM. Industrial, hand tool, and household applications remain strong and steady, and include valve, plumbing, spraying, wrenches, multi-tools, pepper grinders, scissors, circular saws, nailing guns, and similar devices. Automotive applications for MIM started to escalate with use in turbochargers, fuel injectors, control components (clock mounts, entry locks, knobs, and levers), and valve lifters. This initiated in the USA for Buick and Chrysler applications, then expanded to Japan for Honda and Toyota applications, and has grown rapidly in Germany for their auto firms. All expectations are that MIM will continue to grow in automotive. Medical applications are growing from an early base of endoscopic devices, and will become enormous as MIM becomes widely accepted. Much of the recent growth has been in minimally invasive surgical tools and robotic devices. Micro-featured devices are frequently shown for new sensors. These are small devices used for blood testing and disease identification. Dental applications are one of the early successes from MIM, and continues to grow in orthodontic brackets, hand tools, and special endodontic surgical devices. Aerospace applications are accelerating and all of the major aircraft engine firms have embraced MIM. Lighting applications are another growth area, especially in light emitting diode (LED) devices. Sporting applications include metal supports for knee braces, dart bodies, golf clubs, arrowheads, and running cleats. Jewelry applications are new to MIM and are growing as alternative materials become accepted; this includes titanium, high polish stainless steel, tantalum, and even bronze.

Definitions

The following definitions first give the word or phrase commonly encountered in MIM follows by a brief sentence or two on how they apply.

- **acicular powder** - Needle-shaped particles good for debinding strength but they are generally detrimental to the MIM forming process since they resist flow in molding.
- **adiabatic forming -** The use of a frozen powder-water feedstock that melts and flows under pressure, but refreezes when pressure is released.
- **admixed powder** - A small, discrete powder mixed with another powder for lubrication, bonding, or alloying. One common means of forming MIM alloys or composites is via admixed powders.
- **agglomeration** - A tendency for small MIM particles to stick together and appear as larger particles. It is a common problem with nonconductive powders such as ceramics, especially as the particle size decreases.
- **air classification** - A most common means to separate specific size classes of powders by differential settling in a high velocity air stream or cyclone.
- **alloy powder** - A powder in which each particle is composed of the same mixture of two or more constituents, especially common in gas or water atomized powders such as stainless steels.
- **alumina** - The compound of aluminum and oxygen Al_2O_3 that is the most common material used in ceramics, often used as a furnace lining, hardware, or setter support for sintering.
- **angle of repose** - The angle from the horizontal plane that a pile of loose powder will assume when freely poured through an orifice, providing a measure of the interparticle friction and ease of shape retention during debinding.
- **apparent density** - The mass of a unit volume of powder in the loose condition, usually expressed in g/cm^3. For MIM powders it is often 50% of the theoretical density for the material.
- **aspect ratio** - The ratio of the maximum particle dimension to the minimum dimension.
- **atomization** - The dispersion of molten material into droplets by a rapidly moving stream of gas or liquid (usually water), or by centrifugal force. The droplets solidify into particles.
- **atomized powder** - Alloy or metal powder produced by the disintegration and subsequent solidification of a molten metal stream.

- **attrition** - A mechanical milling or grinding process that typically employs a stirred or tumbled container filled with small balls that act as a crushing medium. The tumbling action causes repeated collisions against particles mixed with the balls. The process is widely used for deagglomeration, partial alloying (W-Cu, WC-Co), and particle size reduction in ceramics.
- **austenite -** The face-centered cubic crystal structure of pure iron that is not stable below 910EC. However with alloying this nonmagnetic form of iron can be stabilized at room temperature and even cryogenic temperatures; austenitic stainless steels are a common example where sufficient nickel is employed to stabilize the nonmagnetic phase at room temperature.
- **barrel** - The heated portion of the feedstock flow path before the nozzle. The barrel holds the feedstock under pressure while providing heat to melt the binder system.
- **BET surface area** - The specific surface area as measured by gas adsorption according to the Brunauer, Emmett, and Teller theory. Widely used in characterization of ceramic MIM powders and expressed as square meters per gram, m^2/g.
- **bimodal** - A particle size distribution exhibiting two mode (mode is the most common or most frequent) sizes. Although such a powder can result from mixing two different particle size distributions, some powder production techniques naturally produce this distribution. Its main advantage is in producing a higher solids loading in MIM feedstock. It is common to use trimodal mixtures in ceramic MIM.
- **binder** - The polymer mixture that provides lubrication and strength to the powder. It is critical to the feedstock fluidity during molding and to the strength of the molded compact. The binder is evaporated during debinding and sintering. Binder formulations generally fall into a few classes, but exact formulations are usually proprietary. The binder chemistry impacts the debinding process.
- **Bingham flow** - Viscous flow of a feedstock with initial yield strength, meaning the stress must exceed the yield strength prior to initiation of viscous flow.
- **blending** - The thorough intermingling of powders of the same nominal composition, for example the combination of water atomized and gas atomized stainless steels.
- **brown state -** A term originally used to describe a ferrous MIM component following debinding by slow heating in air to remove the polymer, where oxygen caused the iron to oxidize into a rust-colored component.
- **burnoff** - The removal of the polymer binder via preheating prior to sintering.
- **capillary rheometer** - A device for measuring viscosity by applying pressure on molten feedstock and determining the flow rate dependence on applied stress as the feedstock is pushed through a small capillary tube. It is useful in determining feedstock flow and homogeneity.
- **carbo-nitride** - A heat treatment in a nitrogen and methane atmosphere that causes both carbon and nitrogen to diffuse into the steel surface for strengthening and hardening.
- **carbon control** - A measure of the ability to remove the MIM polymer without contamination of the powder. Carbon control is quantified by the final carbon level and the uniformity of that level between parts, or over subsequent operations, fabrication days, or feedstock batches. For some materials the desire is no final carbon (austenitic stainless steel, alumina, titanium), while others require a precise final carbon level, and in the extreme cemented carbides and silicon carbides require very high carbon levels.
- **carbonyl powder** - Predominantly an iron powder, but may also be nickel. These powders are prepared by the thermal decomposition of a metal carbonyl molecule. The resulting particle size is typically in the size range from 1 to 10 µm. The particle shape can be spherical, agglomerated, or highly angular.
- **carburization-decarburization** - Two events critically related to carbon control, since the addition of carbon to a material occurs by carburization from binder or atmosphere sources, while decarburization occurs by reacting carbon in the material with hydrogen, oxygen, or carbon monoxide.
- **case carburize** - A post-sintering heat treatment aimed at diffusion of carbon into the surface of a ferrous MIM compact. The carbon increases strength and hardness.
- **catalytic debinding** - The partial removal of the polymer via heating in an atmosphere containing an agent that induces depolymerization. The classic process involves extraction of polyacetal using a nitrogen atmosphere doped with nitric acid.
- **CCIM** - Cemented carbide powder injection molding, where the inorganic phase in the polymer binders is predominantly a mixture of cementing phase (cobalt is typical) and a carbide (tungsten carbide is typical); a subset of powder injection molding (MIM).
- **cemented carbide** - A solid composite consisting of a metal carbide and a binder phase, usually cobalt or nickel aluminide. The composite is formed by liquid phase sintering a mixture of the carbide and binder metal powders. The WC composites are known as hardmetals in Europe. They are produced by MIM and used for wear, tooling, cutting, or drilling applications.

- **centrifugal atomization** - The formation of spherical particles by combining a melt with a centrifugal force such that the melt is disintegrated into high velocity droplets which spheroidize prior to solidification.
- **cermet** - A composite body consisting of ceramic particles bonded with a metal. Cemented carbides are the most common cermets in production.
- **CIM** - Ceramic powder injection molding, where the inorganic phase in the polymer binders is predominantly a ceramic or mixture of ceramics; a subset of powder injection molding.
- **clamping force** - One of several measures of the capabilities of a molding machine. In this case the available force for holding the mold together while pressurized feedstock is filling the cavity. If the applied pressure times the projected part area exceeds the clamping force, then the cavity will open or flash during molding.
- **classification** - Separation of a powder into fractions according to particle size.
- **closed-loop feedback control** - A molding concept for precise dimensional control where the pressure inside the molding cavity is monitored during filling and used to adjust the molding machine operation to ensure repeatable filling, weight, and final dimensions. The weight and dimensional scatter in final parts is greatly reduced by using this control logic as compared to open-loop or adaptive controls.
- **closed pore** - An isolated pore not linked to the external surface, usually formed in sintering after a component reaches a density of approximately 92% of theoretical, resulting in capture of the process atmosphere in the pores.
- **coarsening** - The progressive enlargement of the grain size or pore size during sintering due to diffusion, coalescence, or solution-reprecipitation processes. With respect to property control, microstructure coarsening is very important.
- **coefficient of variation -** The standard deviation divided by the mean value, giving a nondimensional measure of uniformity such as in dimensions, weight, or properties.
- **coining** - The final pressing of a sintered compact to obtain a definite surface configuration, flatness, or surface finish.
- **co-molding** - Also known as two-color molding because of the use in plastics. Two materials are shot into the same cavity from different injector units to form layers, interconnections, or other differences in materials with position in the cavity.
- **composite** - A mixture of two or more powders that form a multiple phase structure, typically designed to deliver properties which are a hybrid of the constituent properties.
- **compression** - The removal of air from melting feedstock by applying heat and pressure. In a reciprocating screw molding operation this is achieved by tapering the screw to reduce the space for the feedstock during metering toward the screw tip.
- **computer-aided design (CAD) -** The use of a computer program geared to perform stress, fit, dimensional, and other calculations and to allow visualization prior to fabrication.
- **computer-aided manufacturing (CAM) -** Computer controlled machines used to ensure proper fabrication and resource utilization; included in the broad category of computer integrated manufacturing and computer-aided manufacturing activities might be inventory control, maintenance schedules, production scheduling, tool path analysis, and cost analysis.
- **critical loading** - The maximum volume fraction of solid particles which can be incorporated in a polymer binder without forming pores while still allowing flow in normal injection molding situations.
- **cross linking** - The formation of bonds between polymer chains to give rigidity and strength to the polymer. Thermosetting polymers that harden on first heating are examples of cross linked polymers.
- **cycle time** - A critical measure of molding equipment productivity, it is the time for completion of one molding cycle. It can be measured from the time to start filling to the start of the next fill. Cycle times from a few seconds to 5 minutes are encountered in MIM production.
- **debinding** - A step between molding and sintering where the majority of the binder used in molding is extracted by heat, solvent, catalysis, or other techniques. The debinding techniques are highly variable between production sites. Thermal debinding is most common and the oldest version, but several operations rely on alternatives or combinations of methods.
- **delamination** - The cracking of a molded compact, often leading to a hairline crack oriented perpendicular to the ejection direction that is hidden until debinding or sintering.
- **densification** - The change in porosity divided by the initial porosity due to pressing or sintering. A term loosely associated with property gains in sintering.
- **density** - The mass divided by the volume, usually expressed in g/cm^3 (equivalent to Mg/m^3) or sometimes given as a ratio to pycnometer or theoretical density.

- **dew point** - A measure of atmosphere purity based on water content, it is the temperature where moisture condenses out of a process atmosphere. Generally it is assumed a low dew point (low condensation temperature) corresponds to a cleaner atmosphere.
- **differential scanning calorimetry** – A means to determine the heat flow into or out of a MIM sample. Usually it is applied at lower temperatures where the polymer melts, crystallizes, or evaporates.
- **differential thermal analysis** - The careful measure of temperature and temperature difference during heating for a MIM material and a reference. Whenever the polymer melts or a phase transformation occurs the test sample will lag behind the reference, while if there is a reaction the sample will heat faster than the reference.
- **dihedral angle -** A microstructure feature associated with phase boundaries in a material. It is evident when a grain boundary intersects with a pore or liquid phase, resulting in a groove in the grain boundary at the point of intersection. Low dihedral angles are associated with high grain boundary energies and unstable microstructures.
- **dilatant flow** - Viscosity that changes with flow conditions where the mixture actually dilates under stress.
- **dilatometry** - Measurement of dimensional change during thermal processing to determine the sources of sintering densification, phase transformation, or other causes of dimensional control problems. Usually dilatometry is conducted with a laser or a pushrod that makes contact with the specimen in a furnace. Sintering experiments intended to find the densification temperature for a powder are conducted using constant heating rate dilatometry.
- **dimensional control** - The repeatability of final dimensions in a MIM operation as measured by part-to-part, day-to-day, and batch-to-batch scatter. Usually quantified by the standard deviation (or a multiple of standard deviations, perhaps as large as six) observed in a dimension as normalized by that dimension, expressed as a percent, for example a coefficient of variation of 0.1%.
- **ductility** - A measure of the permanent stretching or deformation a material can take prior to failure. Ceramics have no ductility, while materials such as stainless steel and aluminum exhibit large ductilities, often measured at 30 to 60% stretch or elongation prior to failure**.**
- **ejection** - The final stage of molding where the powder-binder compact is forced out of the die.
- **ejector pins -** Mechanical pins that insert into a die cavity to act as a means to push the molded component out of the tooling.
- **elastic modulus** - The material property linking stress and strain. Also known as Young=s modulus or stiffness. In MIM feedstock it also is important because it determines residual stress and the stress relaxation time in cooling.
- **elasticity** - The spring back of feedstock after ejection from a tool set. Formally, the elastic modulus is the material parameter that links stress to strain, but in MIM it is largely related to die sticking and dimensional control problems since ejection and debinding induce stresses that might cause warpage or loss of component precision.
- **elemental powder** - Powder of a single chemical species like iron, nickel, titanium, copper or cobalt, with no alloying ingredients.
- **elongation to fracture** - A measure of ductility, since this is the amount of permanent plastic stretch a material undergoes prior to failure in a tension test. The most common measure used for ductility.
- **equiaxed powder** - Particles with approximately the same size in all three (perpendicular) dimensions. A sphere formed by gas atomization is the classic example of this desired particle shape.
- **feedstock** - The mixture of powder and binder used in injection molding. Its formulation involves decisions on the powder composition, particle characteristics, binder formulation, mixing practice, and ratio of powder to binder.
- **ferrite** - Various compositions based on iron oxide used to fabricate common magnets, usually containing other metal oxides or ceramics, including zinc oxide. It is also the name given to the body-centered cubic form of pure iron.
- **ferritic steel -** An alloy based on iron that consists of a body-centered cubic crystal structure. It is the most common form of low alloy steel when slow cooled, but is usually heat treated to form martensite.
- **filling** - The first phase of the molding cycle where feedstock is flowing into the mold cavity under pressure from the screw.
- **finishing operations** - The steps applied to a MIM component after sintering to tailor the dimensions, properties, or attributes to the application; examples include machining, polishing, heat treatment, straightening, and electroplating steps.
- **flashing** - A lip of extruded feedstock that penetrates along the parting line of a die cavity due to excessive pressure, poor tool tolerances, or binder separation from the powder.

- **flow analysis** - Computer simulated molding to assess the location of the gate, runner, vent, and cooling passages and other important aspects of tool design and molding to minimize errors in production.
- **flow time** - The time required for a powder sample to flow through an orifice in a standardized test. The flow time gives a measure of the interparticle friction. Most powders used in MIM are not free flowing due to the typical small particle size.
- **fracture toughness** - A measure of the resistance to crack propagation in a material, related to the applied stress when the crack starts moving and the crack size. High fracture toughness materials, such as stainless steels, provide more safety when compared with low fracture toughness materials such as glass or ceramics.
- **freeze firing** - A concept developed in the 1960s using water as the binder and freezing in the tool cavity. The frozen compact is ejected and subjected to sublimation to extract the water without melting the ice.
- **gas atomized powder** - A rounded or spherical powder formed by the disintegration of a melt stream by a high pressure gas expansion nozzle. The particles solidify during free flight after atomization.
- **gate** - The constricted opening into the flow path at the entry to the die cavity in the injection molding tool set. It should be the first portion of the flow path to solidify after filling the mold.
- **gelation** - A binder setting process where a macromolecule grows in a binder solution to form a highly interlinked structure with most of the binder water trapped in cells formed by the long-range molecule.
- **gelcasting -** A variant of low pressure injection molding where the binder consists of a monomer that polymerizes in the die cavity, forming a rigid polymer to hold the particles in place, often supported by a catalyst addition just as the feedstock is molded.
- **granulation** - A term describing the agglomeration of powder or the breaking apart of lumps, runners, sprues, or parts that are reformed into pellets for reloading into the molding machine.
- **green state -** The condition of the molded component prior to debinding or firing. The term comes from the ceramic concept of green ware in reference to formed bodies that are not sintered.
- **green strength** - The strength of the as-molded component at room temperature.
- **guided wave** - An *in situ* inspection technique involving wave propagation through a MIM compact while still in the mold. Mathematical transform of the scattering behavior detects defects, allowing for sorting on ejection.
- **hard material** - A group of compounds that are typically metal carbides, borides, oxides, or nitrides that exhibit a high hardness. To fabricate components, various combinations of the hard materials are combined with cementing metallic phases during liquid phase sintering - for example TiC is sintered with Ni or Fe to form a cermet.
- **hard metal** - Like hard materials, but usually reserved for the WC-Co family of hard materials or cermets. This name for the cemented carbides is more popular in Europe but in general it reflects the high hardness after sintering.
- **hardness** - A formal test of resistance to penetration by a pointed or rounded indenter under a given load. There are many useful hardness tests where the depth or width of the penetration is measured. Often this relates to other material properties such as strength.
- **heavy alloy** - A class of high density alloys based on tungsten with small concentrations of alloying additions such as nickel, iron, or copper. These alloys are liquid phase sintered from mixed elemental powders to create a composite material. Most of the applications are for weights, radiation shields, thermal management heat sinks, or projectiles.
- **hot isostatic pressing** - A process combining temperature and high pressure gas to fully densify a sintered MIM structure. Used only for very high performance structures.
- **hot runner** - A tool cavity where the flow path is kept hot between shots to eliminate recycle of runners and sprues. The built-in heaters and valves are coordinated with the molding machine to ensure no freezing in the flow path.
- **impregnation -** Liquid polymer filling of open pores from an external surface, used to seal open pores after sintering for improved lubrication, corrosion resistance, or machining.
- **Inconel** - A variety of nickel-base alloys invented by International Nickel Company designed for high temperature applications, ranging from furnace components to jet engines.
- **infiltration** - The process of filling the pores of a compact with a lower melting temperature metal or alloy. It is one means of forming low cost tooling or making dense structures via molding a porous preform and filling the pores with liquid metal, such as Al or Cu.
- **injection molding** - A hydrostatic forming technique for shaping powders using plastic binders and relatively low temperatures and pressures.
- **interparticle friction** - The friction between powders which limits sliding, packing, and densification.

- **Invar** - Low thermal expansion alloys of iron-nickel-cobalt where a martensitic phase transformation is balanced against the thermal expansion coefficient to give a near zero thermal expansion coefficient over a range of temperatures.
- **irregular powder** - A powder which lacks shape symmetry in the individual particles.
- **jetting** - A condition that arises with the rapid filling of an injection mold where the feedstock shoots across the mold and fills back toward the gate. Generally this is unacceptable for quality components.
- **knit line** - The same as a weld line. A linear defect occurring where feedstock streams merge in the cavity because of two gates or flow around a core or other solid portion of the die.
- **Kovar** - A glass to metal sealing alloy used for microelectronic packaging and other situations where a matched thermal expansion or graded structure is required.
- **low pressure molding** - The use of lower pressures and low viscosity binders (largely water-based or wax-based) to fill out a complex tool cavity without packing the shape. This route is successful for components where internal flaws are not a concern, such as nozzles, spray tips, or other geometries where external geometry is the key concern.
- **lamination** - A layered structure or cracking in the pressed compact resulting from ejection stresses exceeding the green strength.
- **liquid phase sintering** - Sintering at a temperature where a liquid and solid coexist due to chemical reactions, partial melting, or eutectic liquid formation. It is most useful for stainless steels, tungsten, cemented carbides, cermets, and ferrous alloys containing phosphorus, boron, copper, or silicon.
- **lubricant** - An organic additive which is mixed into the feedstock to minimize die wear and aid in ejection after compaction.
- **maraging steel -** A high strength, high toughness class of iron-nickel-molybdenum alloys that lack carbon, yet form their strength by an age hardening process in the martensitic phase. Strength levels of 4 GPa or 600 ksi are possible with these alloys.
- **martensite -** The distorted ferrite crystal structure (the common variant is a distorted body-centered cubic phase that forms a body-centered tetragonal structure) due to carbon supersaturation in the rapidly cooled ferrite. Martensite is hard and brittle; hence it is usually tempered to partially relax the hard phase for improved toughness.
- **mean size** - The average value from the particle size distribution.
- **mechanical alloying** - The formation of an alloy powder by milling elemental powders for a prolonged time; frequently used to create amorphous or dispersion strengthened alloy powders via attritor milling.
- **median size** - The centroid of the particle size distribution, where half of the particles are larger and half are smaller; not necessarily the mean, but easily identified as the 50% value. Also known as the D_{50} particle size.
- **melt index** - A measure of flow at low shear strain rates, where a capillary tube is used to extrude molten feedstock under a dead load. The melt index depends on the capillary tube diameter and applied load, but is always reported as the grams of feedstock collected from the tube in 10 minutes.
- **metering** - Controlled forward extrusion of molten feedstock past the screw tip and check ring to ensure the proper shot volume is ready for the next filling event.
- **microminiature -** Component dimensions measured in the micrometer size range, requiring microscopes for evaluation. These are typically formed using special machines with smaller shot size to enable better precision for small bodies.
- **micromolding -** A new class of MIM technologies geared to the production of components in the millimeter and micrometer size range, requiring new technologies in tool fabrication, nanoscale powders, and molding machine operation and construction. Most of the early applications are in microelectronics, medicine, sensors, and optical communication systems,
- **microstructure** - The detailed information on the microscopic phases, pores, grains, defects, heterogeneities, and other property controlling features.
- **MIM** - Metal powder injection molding, where the inorganic phase suspended in the binder is predominantly a metal or alloy powder. Common engineering alloys are possible by mixing elemental powders and forming the alloy during sintering (homogenization) or by use of a prealloyed powder where each particle contains all of the elements. MIM is a subset of powder injection molding (MIM).
- **mixing** - The thorough intermingling of powders of two or more different compositions. It is also used to describe the compounding of feedstock by the thorough distribution of binders between particles.
- **mold flow simulation** - The use of computer simulations for analysis of the flow, packing, venting, sizing, cooling, and other events and tool or machine parameters associated with MIM forming operations.

- **mold release** - A spray or coating that reduces component sticking to the die cavity, aiding ejection without defects.
- **moldability** - A relative measure of the ease of filling out a tool cavity during injection molding. It can be determined by the length of filling for a long, narrow passage. The current test of plastic moldability is to measure the filling of a spiral, which has been altered in MIM to a zig-zag fill test to induce powder-binder separation along the flow path.
- **multimodal** - A powder size distribution which exhibits several modes, possibly generated by blending several monosized powders.
- **nanoscale** - Powders or microstructures with sizes that can be measured in nanometers. Typically the powders are less than 100 nm in size, or less than 0.1 μm.
- **near net-shape -** Many production technologies, including MIM, attempt to form a discrete component without a need for final machining. Together these technologies are considered net-shape approaches, but when critical dimensions cannot be held without a final machining step they are termed near net-shape technologies.
- **net-shape** - A compact manufactured to final density and dimensions without the need for machining. MIM is a net-shape process.
- **Newtonian flow** - An idealized viscosity situation applicable to a few fluids where there is no sensitivity to the shear strain rate, only temperature. The stress is proportional to the shear strain rate.
- **nodular powder** - Irregular particles with knotted, rounded shapes. This is characteristic of water atomized powders.
- **open pore** - A pore completely through a compact from one surface to another. During thermal debinding the pores must be open to allow the escape of evolving vapors. Open pores close in sintering at a density near 92% of theoretical.
- **oxidation-reduction** - A combination of atmosphere-powder reactions that can extract oxygen (reduction) or deposit oxygen (oxidation) in a powder compact during heating, especially during debinding and sintering. Reduction conditions are usually required for sintered metallic materials.
- **packing pressure** - The peak pressure encountered in the molding operation once the die is filled, prior to freezing of the gate. It is precisely controlled for weight uniformity and optimized final dimensional control.
- **particle size** - The controlling linear dimension of an individual particle, as determined by analysis with screens, lasers, or other sensing techniques.
- **particle size analyzer** - An automated device for determination of the particle size distribution. These are widely used in the research, product development, and quality control functions as part of MIM to ensure repeatable powders for the process.
- **parting line** - The linear mark on a compact where two separate tool or die pieces mated during shaping. In injection molding it is where the two halves of the die joined together.
- **pelleting** or **pelletizing** - The formation of discrete chunks of feedstock with repeated sizes and shapes that allow easy flow and filling of the molding machine.
- **PIM** - Powder injection molding is the comprehensive term for forming inorganic engineered components in a plastic molding machine using thermoplastic binders and inert powders, with subsets including metal powder injection molding (MIM), ceramic powder injection molding (CIM), and cemented carbide powder injection molding (CCIM).
- **planetary mixer** - Usually these have two offset mixing blades that rotate around individual shafts and the two blades further rotate around a center axis. The net effect is intermixing and stirring and shear to produce MIM feedstock, usually in a heated vessel.
- **plasma debinding -** A new technology similar to catalytic debinding it involves a low pressure plasma for depolymerization of the binder from the sample surface inward to avoid heating and softening for distortion control.
- **plunger molding** - A hydraulic plunger is used to push molten MIM feedstock into a die cavity, where motion and pressure are controlled by the applied hydraulic pressure.
- **pneumatic molding** - Use of an air pressure head over molten feedstock to push it into a die cavity. This is the lowest cost and least precise form of MIM, yet is widely employed in the fabrication of large ceramic structures.
- **polydisperse** - Implies a broad powder size distribution, covering a wide range of particle sizes with no clear mode size.
- **pore size** - The size of the holes or voids between powder particles, often measured by microstructure quantification, mercury porosimetry (open pores only), or other tests that include gas flow, gas condensation, and polymer intrusion.

- **porosimeter** - A device for measuring the size of the open pores using high pressures and mercury intrusion techniques.
- **porosity** - The amount of void space in a powder compact. Most MIM materials have less than 5% porosity after sintering.
- **powder** - Particles of solid matter characterized by a small size, less than 1 mm in size. Most MIM powders are below 20 micrometers in maximum size.
- **prealloyed powder** - Each particle contains an intimate mixture of two or more elements in a prescribed ratio to form an alloy; examples include brass, bronze, steel, and stainless steel.
- **presintering** - The heating of a compact to a temperature lower than the normal sintering temperature to gain strength for subsequent handling, including machining. This is often performed by heating above the highest temperature required to thermally decompose any residual binder polymer.
- **pressure-assisted sintering** - Sintering with the application of an external pressure. It is often performed by initially sintering in vacuum and subsequently pressurizing the furnace to densify any remaining closed pores. Best applied to high performance alloys or difficult to sinter alloys and is commonly employed for nitrides that decompose during sintering (AlN and Si_3N_4) and brittle materials that require full density (WC-Co for example).
- **pressure control** - The final phase of molding where the gate is not frozen and the quantity of feedstock in the die cavity is controlled by the pressure, thereby ensuring uniform weight and dimensions in the final MIM component. Proper control is achieved by monitoring pressure sensors in the die cavity wall.
- **pseudoplastic flow** - A form of viscous flow where there is a strain rate sensitivity to the viscosity; generally it is the opposite from dilatant flow, since the viscosity decreases with higher strain rates.
- **pycnometer** - A device for measuring the theoretical density of a loose powder or preform. Helium and granular Afluids@ are commonly employed to encase the powder or component for determination of true volume, and when coupled with an independent mass determination leads to a density.
- **PZT** - Piezoelectric ceramic based on oxides of lead (Pb), zirconium (Zr), and titanium (Ti) used for ultrasonics, sensors, sonar, and various signal propagation or collection applications, based on shapes fabricated by MIM.
- **rapid prototype -** Several techniques emerging that bypass a need for tooling by using computer controlled freeform fabrication to generate a first MIM green body, typically via building the feedstock into a three-dimensional object from a stack of closely spaced laminates.
- **reciprocating screw** - Injection molding with a screw located in a heated barrel. During compression, metering, melting, and forward advance of the feedstock, the screw is turning, while during mold filling it becomes a plunger to quickly fill the cavity.
- **reduced powder** - Metal powder produced by the chemical reduction of a compound, most typically a metal oxide.
- **refractory** - A metal or ceramic having a high melting temperature, usually over 1700EC. Example refractory metals are tungsten, molybdenum, rhenium, and zirconium, while example refractory ceramics are alumina, zirconia, yttria, and chromia.
- **rheology** - The study of strength, elastic, plastic, and viscous flow of polymers and feedstocks used in MIM.
- **runner** - A portion of the feed path for filling an injection molding die; the runner is between the sprue and gate, the latter being the inlet to the actual die cavity.
- **screw** - The key portion of an injection molding machine for metering and filling the die cavity. It has a taper along the length to compress the feedstock as it is metered for removal of trapped air and a check ring at the tip to allow forward plunging motion during mold filling.
- **screw molding** - A reciprocating screw is used to mix, pressurize, deair, and convey molten feedstock to finally be injected into a tool cavity. This is the most widely employed means of injection molding precise components.
- **secondary operations** - Those activities performed to adjust dimensions or properties of a component after sintering. Examples include heat treatment, coining, machining, electroplating, impregnation, and shot peening.
- **segregation** - Nonuniform distribution of ingredients, such as powder separation by size, shape, or density, or chemical separation in the microstructure of a solidified material.
- **Sendust** - Alloys of iron-aluminum-silicon that have important combinations of hardness and magnetic properties suitable for magnetic card readers and other high use magnetic applications. The alloy hardness is such that MIM is the most credible manufacturing route.
- **setter -** The tray or shaped substrate for support of MIM compacts during debinding and sintering.

- **shear rate** - A measure of the rate feedstock is deformed and forced to flow into a die cavity. It has units of inverse seconds. Actually it is the shear strain rate, representing the sheared change in length divided by the original length in unit time. For MIM shear rates of several thousand per second are normal, meaning the slug of feedstock is quickly deformed to fill out the cavity.
- **shot size** - A historical basis for sizing molding machines. This is usually given in terms of the amount of polystyrene that can be moved through the nozzle in a single forward motion of the screw or plunger.
- **shrinkage** - A decrease in dimensions of a compact which occurs during sintering, usually 15% or up to 25% in a few cases and as low as 2% with multimodal powders.
- **SiAlON -** A group of commercial alloys based on silicon nitride, with liquid phase formers such as alumina and yttria. These are very strong and lightweight materials with exceptional strength and reasonably high temperature properties (up to 1200EC) useful in high temperature aerospace, diesel engine, and military systems.
- **sigma mixer** - A closed mixer consisting of two blades that look like the Greek capital letter sigma. These blades lift and separate feedstock to form a mixture of moderate homogeneity. A major advantage for MIM is the small batch size, but with low homogeneity due to the poor shearing.
- **silicon carbide -** The man-made compound SiC that is used for applications ranging from sandpaper to high temperature heating elements. It has excellent high temperature strength and oxidation resistance and is formed by MIM when complex shapes are required without post-sintering machining. Most systems rely on boron and carbon additions to improve sintering.
- **silicon nitride -** Compositions based on the stoichiometric compound Si_3N_4; in MIM this compound is used with various liquid phase sintering additives to form SiAlON compositions.
- **sink mark** - A shallow surface cavity that forms during cooling. It is usually indicative of under packing prior to gate freezing and is corrected by a higher molding pressure.
- **sinter harden** - Controlled cooling from the sintering temperature designed to induce desirable transformations and microstructures, to avoid post-sintering heat treatments. Usually it is applied to ferrous alloys to control martensite formation on cooling.
- **sintering** - The thermal process which bonds and densifies the molded powders. It increases the compact strength via diffusion or related atomic level events. Most of the mechanical, magnetic, or other properties of a MIM part are developed in the sintering cycle.
- **sintering diagram** - A process map showing the interaction of the key variables with respect to the densification of a powder. The variables include particle size, grain size, temperature, time, and applied pressure.
- **solids loading** - The relative powder volume in feedstock designed for binder-assisted shaping. Common injection molding feedstocks have solids loadings near 0.6 or 60 vol. % powder.
- **solvent debinding** - The extraction of the binder or some portion of the binder by leaching into a solvent. This is performed by immersion or exposure to solvent vapors. The solvent might be flammable, toxic, or simply water or ethanol.
- **speed control -** That initial portion of the molding cycle where feedstock is flowing to fill the mold cavity and no feedback signals are available; thus the molding machine is simply controlled by the position of the screw during its forward (injecting) motion.
- **spherical powder** - Powder with a uniform spherical shape and a size that can be characterized by a diameter. Gas atomized powders are often spherical.
- **sprue** - The initial inlet into the die set for injection molding feedstock. The sprue is usually filled by the nozzle and is tapered for easy extraction after mold filling. It feeds the runner system, which in turn feeds the gate.
- **stainless steel** - A wide range of alloys based on iron and chromium that give corrosion resistance in most common corrosive environments. The most popular MIM alloys are 300 series (austenitic) that contain high nickel levels, 400 series (mostly ferritic or heat treatable into martensitic) that have little nickel, and precipitation hardened alloys (mostly heat treated into martensitic) such as 17-4 PH.
- **stereolithography -** A group of rapid prototype techniques that construct a green MIM component from a computer design by building thin sequential layers that match cross-sections through the design, typically using laser, ink jet, cutting, or micro-nozzle concepts.
- **stress relaxation** - The removal of residual stresses in a MIM component by controlled cooling or reheating to relax the polymer entanglement or other sources of stress.
- **superalloy** - The highest performance alloys used for the most demanding applications. Typically these are formulated with a wide range of components, based on nickel, with tailored properties that allow use in moving components in jet turbines.

- **supercritical extraction** - The use of high pressure and moderately high temperatures to heat a solvent over the critical point for binder removal. The most common supercritical fluid used in MIM is carbon dioxide. Over the critical point the gas is compressed to a density equal to that of the liquid, so there is no volume change on binder removal.
- **supersolidus sintering** - A liquid phase sintering process applied to prealloyed powders where sintering occurs over the solidus temperature, thereby nucleating liquid within the particles to enable rapid densification of larger particles. It is used for high alloy systems, such as tool steels, stainless steels, cobalt-chromium alloys, and superalloys.
- **surfactant** - A surface active agent added to the binder system in MIM feedstock to induce binder wetting of the powder surface. There are many trade secrets, but most powders prove responsive to simple soap compositions.
- **tap density** - The density of a powder obtained when it is vibrated for a prolonged period. The tap density represents the highest packing density possible for a powder without the application of pressure.
- **tensile strength** - The maximum strength attainable prior to failure during uniaxial tension testing; properly known as the ultimate tensile strength, but often given as the tensile strength.
- **thermal debinding** - Extraction of the polymer in debinding by the application of heat. The classic processes relied on slow heating in air to evaporate the binder over a period of days.
- **thermogravimetric analysis** - A term that means measuring the sample weight change versus temperature during heating. It is used for determination of polymer evaporation temperatures by performing constant heating rate experiments and recording the sample weight versus temperature.
- **thermoplastic** - Binders or polymers (like wax) that soften on heating, but stiffen on cooling, and can repeat the heating and cooling process without undergoing degradation.
- **thermosetting** - Binder or polymer hardening due to heating to a temperature where crosslinks form between the polymer chains. Unlike a thermoplastic that can be softened by reheating, a thermosetting binder becomes hard on the first heating cycle and cannot be subsequently softened.
- **thixomolding** - A direct injection molding technique that is a hybrid between powder injection molding and die casting. The alloy is partially melted to form a solid-liquid mixture that is initially stiff, but with continued stirring becomes low in viscosity and easily molded. Many MIM operations had hoped for an aligned benefit for thixomolding lower temperature alloys and lighter weight alloys. Currently only magnesium alloys are commercial, but aluminum and titanium variants have been demonstrated.
- **thixotropic** - A material flow behavior where there is a yield strength that must be overcome to initiate flow and with shear the viscosity decreases; however, during aging weak bonds form to increase viscosity.
- **torque rheometer** - A computerized mixer that allows interactive experiments to measure the torque for mixing as various changes are made in surfactants, powders, binders, temperature, or shear rate. The output from the torque rheometry provides an effective basis for formulation of MIM feedstocks.
- **toughness -** Literally the energy to cause failure or fracture per unit of test material cross-sectional area. It can be estimated by the product of strength and ductility, but is more typically measured using a swinging pendulum that fractures a standard test sample (Charpy test). The kinetic energy loss by the pendulum is the toughness. In design, the most important parameter is the fracture toughness, which measures the stress required to cause a crack to propagate.
- **transverse rupture strength** - Three-point fracture test applied to brittle materials or green compacts to assess relative strength. The three-point bend test configuration is most common for these materials with a four-point test sometimes used to measure the strength of sintered ceramics.
- **twin screw processor** - A mixer or extruder consisting of two intermeshing screws which convey, shear, and mix a powder or powder-binder mixture during transport through the mixer.
- **ultimate tensile strength** - The highest engineering stress encountered in the tensile testing of an engineering material.
- **ultrasonic inspection** - The use of high frequency sound waves for detection of cracks or other defects. The most common procedure uses through or back transmission waves out of the die cavity, but new technology allows guided wave inspection in the die cavity during molding.
- **vacuum debinding** - A variant of thermal debinding that gives extraction of binder by progressive heating in a vacuum to distill the molten binder out of the powder compact. Usually vacuum debinding is performed with a gas inlet to drag escaping binder to the pumps.
- **vent** - The thin channel in a tool set that allows air to escape while molten feedstock enters through the gate. It is located opposite from the gate and should not be sealed until late in the molding cycle to avoid trapped air pockets in the component.

- **viscosity** - The resistance to flow of a feedstock or polymer. Formally it is the proportionality between the stress and applied shear strain rate. A high viscosity makes molding difficult. A low viscosity is easier to mold, but there are often difficulties with flashing.
- **water atomized powder** - Irregular or ligamental particles formed by impacting a molten metal stream with high pressure water.
- **water-based binder** - Mostly gelation binders that become rigid after molding by the formation of a long-range molecule with water in the structure. Other forms rely on water saturated with silicates that form glasses on freezing.
- **water soluble binder** - A class of binders that rely on polymers that are water soluble so solvent debinding takes place in water. Most common are polyethylene oxide, polyvinyl alcohol, and polyethylene glycol.
- **wax-polymer** - A general term for polymers used as binders that consist of low molecular weight polymers and wax fillers. The polymers are usually simple molecules such as polyethylene, polypropylene, or co-polymers such as ethylene vinyl acetate. These are the classic binders used in MIM processing.
- **weld line** - A linear defect or mark on a compact surface where two portions were bonded, either in molding or subsequently, such as in sinter bonding.
- **Weibull modulus** - A statistical parameter associated with the spread in fracture strengths for ceramics. A high Weibull modulus indicates a narrow spread in strength and few manufacturing defects.
- **wicking debinding** - The most popular means of binder extraction, especially for wax-based binders, where the compact is packed in wicking powder and heated to a temperature where the wax melts. The molten wax flows by capillary action into the surrounding packing powder and leaves the compact supported as polymer is extracted.
- **yield strength** - The end of the linear elastic region for most metals. The yield strength is the highest stress a structure can endure without permanent deformation and should be the maximum stress used in engineering designs.
- **Young=s modulus** - The elastic modulus expresses the proportionality between stress and strain during elastic deformation prior to permanent deformation; it is calculated assuming linear behavior by dividing the applied stress by the strain and for metals such as steel can range near 200 GPa (30,000,000 psi).
- **YTZ** - Yttria toughened zirconia, where a few percent of Y_2O_3 is added to ZrO_2 to help in phase stabilization such that a phase transformation occurs in the zirconia under severe stress, such as at a propagating crack tip, to block fracture.
- **zeta potential** - An electrochemical measure of the surface charge or surface chemistry of a fine powder in a suspension.
- **zirconia** - A stoichiometric compound of zirconium and oxygen in the ratio ZrO_2. It is often phase stabilized by adding other ceramics. It is widely employed as a MIM material because of its exceptional wear resistance and difficulty in grinding, and is colored to form a wide variety of semiprecious jewelry items.

Misconceptions

Many engineers think of MIM as a new field. In many regards it is new, but various forms of the technology have been in commercial use since 1975. Over the 35 years MIM has been in practice, some folklore has arisen, leading to some broadly held misconceptions. This section identifies a few of these misconceptions and helps clarify some of the common myths.

Special molding machines are required.

Certain molding machine characteristics are better suited to MIM, especially for higher levels of precision, but many firms are successful with a variety of molding machines. The evidence suggests that there is no single manufacture or design that is necessarily best.

There is easy money to be made in MIM.

With its maturation, MIM has largely remained a healthy technology that continues to grow by satisfying more sophisticated customers. But most of the firms with favorable financial positions tend to have much practical experience, and almost all of the leaders are well over 10 years old.

These leaders have established manufacturing systems which are benchmarks for all net-shape manufacturing. To assume that a late entry will jump into this class is not realistic. Yes, there is success if you work long and hard, but MIM is not a route to quick riches.

Only a few firms understand the technology.

There are about 400 firms, several university programs, and a dozen research institutions supporting the technology developments in MIM. None of these has a lock on the technology. The basic concepts are well documented in books, and many of the suppliers will gladly share technology to help create new customers. As is often known as Prado's Principle, 20% of the firms have 80% of the sales, but it is not wise to assume any single firm is smarter or more knowledgeable than another. The field has many successes, failures, and much cross-fertilization, so there is no single pathway or technology that will give success.

A license is required to practice MIM.

Some of the first commercial developments in powder injection molding date from the 1930's and 1940's, so long ago we have trouble reconstructing the history. In the 1960's, Corning used ceramic molding to form tableware, a technology that survives in the ceramic casting core business. In MIM, the original patents were issued in the 1970's. Thus, with the technology aging this much, many of the suppliers provide an excellent support base for start-ups. The generic technology works well and most of the ingredients and equipment can be ordered with help from the equipment manufacturers. So, if a company wants to have its hand held during the start-up phase using a license, that is fine, but to think there is a proprietary or special technology that requires a license does not reflect reality.

Molders that purchase the same feedstock allow for movement of an order between sites.

Clearly, a trend has been to rely on purchased feedstock, but that does not cure the need for similar molding practices, processing equipment, and secondary operations. In general, tool design is highly variable and customized to the shop and molding machine. Hence, moving an order to a second site might encounter problems beyond the feedstock, so there is no assurance of success along these lines.

You need a materials scientist to succeed.

This is a myth that is close to reality in some cases. Several plastic injection molders have successfully entered MIM, but at times they struggle with controlling impurities, optimizing properties, selecting proper heat treatments, and other basic aspects of materials engineering. These can be mastered without full-time staff. One start-up used a skilled metallurgist on an as-needed basis. Another plastic firm initially relied on feedstock and furnace vendors for support. A plastic molder in Canada used a network of small contracts to seed critical developments during start-up. However, to become established at more than say $5 million in annual sales requires mastery of three technologies - materials engineering, manufacturing engineering, and plastic molding, but you can start with only one or two.

Powder costs will continue to fall.

As MIM grows, some of the powders (especially prealloyed stainless steel) have declined in cost as consumption has increased. But in all cases, consumption has increased faster than the cost reduction. In other words, if powder sales (dollars) have increased 20% per year then powder shipments (tons) went up 40% per year. Along with improved process yields, the increasing tonnage generated a price decrease. For some alloy chemistries this sort of volume growth is not going to be sustained.

Low pressure molding is less costly.

Low pressure MIM machines are used to reduce machine cost and tool wear. They are used by about 15% of the combined metals and ceramics industry. The manufacturing cost is now lower with low pressure molding, since these options lack automation and usually only fill a single cavity. So with a lower purchase price (capital cost) there is a burden of a higher operating cost. For example, in a comparison across the industry, low pressure molding shops show lower sales per employee. More important, without a high molding pressure the components tend to have more internal defects. For surface features (such as in sand blast nozzles and watch cases) there is no problem.

Continuous sintering in hydrogen is a MIM evolution.

The use of hydrogen sintering in a pusher furnace was applied to refractory metals and stainless steel prior to the 1940's. It was widely used for that application at many sites prior to the first commercial MIM use in 1985. Today, continuous furnaces constitute about a quarter of the installed sintering capacity in MIM and prove most productive for long-running components. Thus, they are more common in large Asian shops fabricating consumer products, cellular telephone parts, and watch cases.

The MIM technology is only capable of holding tolerances at ±0.5%.

High tolerances are always possible using post-sintering machining. The real challenge is in forming tight tolerances without coining or machining. The as-sintered tolerances depend on the age of the technology, recognizing newer operations employing better binders, molders, and process control during debinding and sintering processes. Essentially all of the industry can hold dimensional scatter to within ±0.3% (one standard deviation), but a few have reached a coefficient of variations as small as ±0.02% with newer controls, such as closed loop feedback control during molding. A few products are in production with absolute tolerances of ±2 to 5 μm.

Newer binders enable cost-effective production of large components.

The binder is not a barrier to molding large components. Large stainless steel components were formed in the 1980s using MIM, ranging up to 12 kg (26 lb), using a traditional wax-polymer binder. Today large ceramic components are in production at several sites. There are problems with large components, but more significant are the economic barriers. In metals, as the mass increases the raw material cost difference (powder versus casting cost) leaves plenty of margin for machining after casting. Thus, changing the binder will not solve the critical powder cost issue. Indeed several economic problems arise with large MIM components, besides powder cost there are penalties because the molding machines are larger, molding cycles are slower, and debinding times are longer. Accordingly, MIM is less cost-effective as size increases, independent of the binder.

Metal powder injection molding is just another form of powder metallurgy.

Although a few companies practice both MIM and traditional die compaction and sintering (what is generally implied by the term powder metallurgy). The two technologies have little in common other than utilizing metals powders. MIM powders are much smaller, round if not spherical, and sintering temperatures are higher such that the final density and performance are much better. The only thing these two technologies have in common is powdered metal and a sintering process. But the size of the powdered metal particles and the sintering processes vary significantly.

Standards

The standards used in MIM usually start at the national level, say in Japan or the USA, and then become adopted in the powder community, and spread to national bodies, eventually becoming part of the ISO standards. For North America, the example would be the MPIF or Metal Powder Industries Federation as the regional trade organization, which then feeds its standards into the ASTM or American Society for Testing Materials, which participates in the ISO or International Standards Organization global standards. The standards are reviewed and updated periodically, and expanded to handle new alloys, processing options, or test parameters. Listed below are some of the ones seen in MIM.

Testing Powders

Analysis by Microscopical Methods for Particle Size Distribution of Particulate Substances of Subsieve Size - ASTM E20
Apparent Density of Non-Free Flowing Metal Powders Using the Hall Apparatus - MPIF 04, ASTM B212, ISO 3923/1
Apparent Density of Non-Free Flowing Metal Powders Using the Carney Apparatus - MPIF 28, ASTM B417, ISO 3923/1
Apparent Density of Metal Powders Using the Arnold Meter - MPIF 48, ASTM B703
Apparent Density of Refractory Metals and Compounds by Scott Volumeter - ASTM B329
Average Particle Size of Metal Powders Using the Fisher Subsieve Sizer - MPIF 32, ASTM B330, ASTM C72 (see also ISO 10070)
Flow Rate of Free-Flowing Metal Powders Using the Hall Apparatus - MPIF 03, ASTM B213, ISO 4490
Oil Absorption of Pigments by Spatula Rub-out - ASTM D281
Particle Size Distribution of Metal Powders and Related Compounds by Light Scattering - ASTM B822
Particle Size Distribution of Refractory Metals and Compounds by X-ray Monitoring of Gravity Sedimentation - ASTM B761
Particle Size Distribution of Tungsten Metal Powder by Turbidimetry - ASTM B430
Sampling Finished Lots of Metal Powders - MPIF 01, ASTM B215, ISO 3954
Tap Density of Metal Powders - MPIF 46, ASTM B527, ISO 3953

Testing of Sintered Products

Carburized Case Hardness and Case Depth of Sintered Parts - MPIF 37, ISO 4507
Density Determination of MIM Components (Gas Pycnometry)- MPIF 63
Determination of Charpy Impact Energy of Unnotched Metal Injection Molded Test Specimens - MPIF 59
Determination of Corrosion Resistance of MIM Grades of Stainless Steel Immersed in 2% Sulfuric Acid Solution - MPIF 62

Green Strength of Compacted Metal Powder Specimens - MPIF 15, ASTM B312, ISO 3995
Impact Strength of Sintered Metal Powder Specimens - MPIF 40, ISO 5754
Material Standards for Metal Injection Molded Parts - MPIF 35
Nickel-Iron Powder Metallurgy Soft Magnetic Alloys - ASTM A904
Nickel-Silver Sintered Metal Powder Structural Parts - ASTM B458
Sintered Austenitic Stainless Steel Structural Parts - ASTM B525
Sintered Metal Materials and Hardmetals Determination of Young's Modulus - ASTM E111, ISO 3312
Sintered Metal Materials, Excluding Hardmetals, Determination of Transverse Rupture Strength ISO 3928
Soft Magnetic Iron Fabricated by Powder Metallurgy - ASTM A811
Standard Specification for Metal Injection Molding (MIM) Ferrous Parts - ASTM 883
Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push-Rod Dilatometer - ASTM E228
Transverse Rupture Strength of Sintered Metal Powder Test Specimens - MPIF 41, ASTM B528, ISO 3325

Patent Sources

There are a large number of patents in MIM, dating from about the mid-1970s. The easy means to sort through the US Patents is via the web site www.uspto.gov and enter the quick search for patents zone (PTO = patent and trademark office). You can search by title, key word, inventor, year, or other features. Be careful in relying on "MIM" since this has many other definitions besides metal powder injection molding. Once a patent is identified, a good copy is available as a PDF file at www.pat2pdf.org as a free download.

Conferences and Publications

Every two years there is a World Congress of Powder Metallurgy, rotated between Asia, Europe, and North America. This is the typical forum for showing the latest developments in MIM. Additionally, regional trade organizations organize annual conferences and MIM is usually well represented at these. To give focused attention on MIM, a short course and table top exhibition, standards committee meeting, technical presentations, and company capability briefing is organized, usually in a desirable location, such as Orlando or San Diego or Los Angeles. While the World Congress will often draw 1500 participants, the regional conferences are about half that, and the MIM topical meetings attract typically 150 participants.

Trade and Professional Organizations

There is no trade association specifically for MIM. Powder metallurgy trade associations embrace MIM as part of their activities, including coverage at annual conferences, articles in the magazines, and training courses. The trade associations focused on powder metallurgy are as follows:

European Powder Metallurgy Association, Shrewsbury, UK – www.epma.com
Japan Powder Metallurgy Association, Tokyo, Japan – www.jpma.gr.jp

Metal Powder Industries Federation, Princeton, NJ, USA – www.mpif.org

In addition a new Asian Powder Metallurgy Association combines the separate organizations in Japan, Taiwan, South Korea, and China. Many other countries have small efforts, for example in Turkey, South Africa, Russia, and Thailand.

Summary Points

MIM has exhibited enormous growth since the first sales statistics were gathered in 1986. Today, MIM continues to grow and is sustaining 14% per year growth. The number of MIM firms has stabilized as the industry sophistication has grown. Various estimates have been offered for how far and how long MIM can sustain the growth. The informed estimates balance cost, capacity, and competitive factors, but generally agree MIM will double yet again to reach $2 billion in annual sales by 2017. Many design engineers are still discovering the field.

It is not uncommon to see a 30% cost reduction in switching to MIM. In several cases, cost has been reduced by 90% from that of the machined component. For example, a surgical biopsy device dropped from $27 each to $2.70 each on switching to MIM. Further, new shapes and design features have pushed MIM into applications where there is essentially no competing technology. Much information, more details on the technology, and many other illustrations of applications are available – a good starting point is the book by Randall M. German, *Metal Injection Molding – A Comprehensive MIM Design Guide*, available from the Metal Powder Industries Federation, Princeton, New Jersey, at www.mpif.org. The electronic version (sold on compact disk) has all of the illustrations in color, while the print version is black and white.