METAL INJECTION MOULDING (MIM)

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Introduction

- **History**
  - The idea to plastify powdered raw materials with the help of thermoplastic additives and subsequently using injection moulding to form complex components was first developed in ceramics technology.
  - 1970's : Raymond Wiech (USA) was adapted this process to metal powders .
  - He is widely considered the inventor of the new metal forming process which was named **metal injection moulding.**

Introduction (Cont.)

- **Growth**
  - MIM applications are growing at a rapid rate with an increase of over 80% in the tonnage of metal injection moulded parts shipped in the period 2003 to 2006, with current sales estimated to be in excess of $1billion.

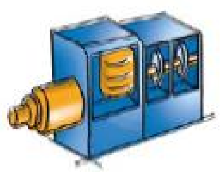
Process

Manufacturing process metal injection moulding technology (MIM)

Metalpowder

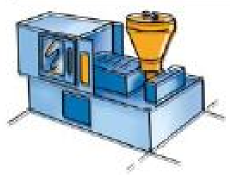
Finest metal powders or metel powder alloys

Mixing



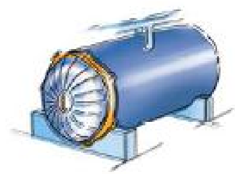
Powders are mixed with thermoplastic plastic binder (Feedstock)

Injection moulding



Shaping via injection moulding. The feed stock is injected into moulds (dies), creating the socalled green component

Debinding



The binder is removed from the green component using applicable processes (e.g. thermal or chemical)

Sintering

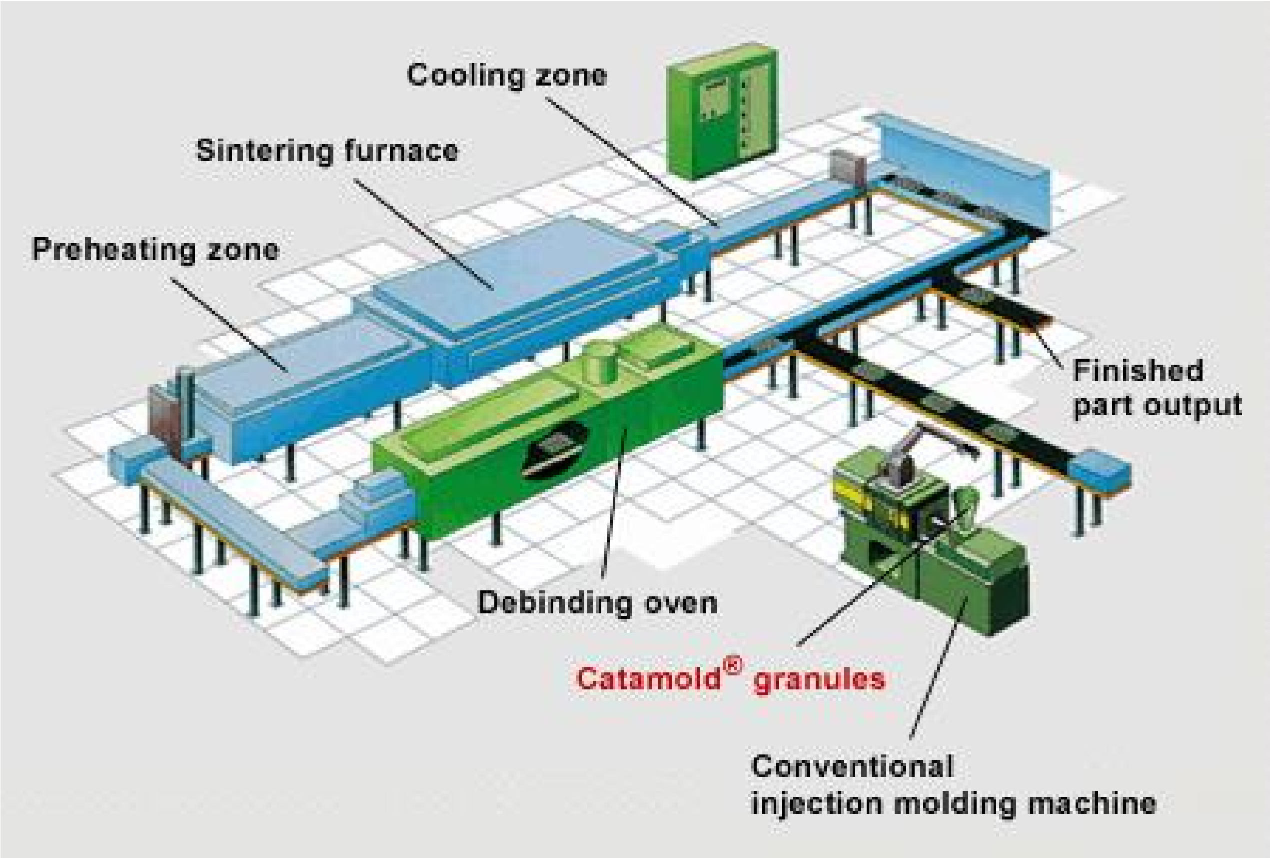
The materials are sintered in a heat treatment process. The material characteristics are comparable to those of compact materials

Processing

Finally, the surfaces of finished MIM parts are processed as required

Process

Diagram of a fully continuous production line showing the three main process stages: injection molding, debinding and sintering.



Process : Metal Powder

- A **wide range** of materials for MIM is available and more are being developed.
- **Low alloy steels** and **stainless steels** are the most in MIM materials produced today.
- The densities of MI moulded alloys are usually 96% of full density or higher.
- The microstructures are **isotropic** (i.e. equal material properties in all directions) and free from nonmetallic impurities.
- Residual pores are isolated, very fine and spherical - metal injection moulded materials generally have much higher strength properties than cast or wrought alloys of the same composition.
- The metal powders used in MIM are usually at least one order of magnitude finer than the powders used in die compaction.

Process : Metal Powder

- **Low alloy steels**
  - Often based on carbonyl iron powder which is composed of spherical particles with particle sizes between 1 and 10 µm.
  - Alloys are formed by mixing the base powder with carbonyl nickel and other alloy constituents.
  - These low alloy steels are often quench-and-temper heat treated or case hardened after sintering and attain high hardness and strength levels combined with a high ductility and fatigue strength.
  - MIM-4140 and MIM-4340 are the standard grades for this class of metal injection moulding alloys.

Process : Metal Powder

- **High alloy materials**
  - High alloy materials such as stainless steels (MIM-316L) are usually made from gas or water atomised alloy powders with particle sizes of less than 40 µm.
  - Gas atomised particles are spherical, water atomised powders have irregular particle shapes.
  - There is no general rule whether spherical or irregular powders are better suited for MIM
  - The hardness or ductility level, respectively, can be varied continuously depending on the requirements of the application.

Process : Metal Powder

- **Special steels**
  - The wide range of ferrous metal injection moulded alloys used for structural components also includes hardenable stainless steels like the precipitation hardening MIM-17-4 PH and iron-chromium-carbon alloys with 13% and 17% chromium.
  - Tool steels and high-speed steels are manufactured by metal injection moulding as well. Many soft magnetic alloys like iron-phosphorus, iron-silicon, iron-nickel and iron-cobalt alloys, Invar and Kovar are also available in high quality as metal injection moulding materials.

Process : Metal Powder

- **Non-ferrous materials**
  - Particularly attractive due to its high strength, light weight, corrosion resistance, and potential cost savings is titanium. Some specialized metal injection moulding producers are able to manufacture parts from titanium alloys such as Ti6Al4V or Ti6Al7Nb with an oxygen content below 2000 ppm. Titanium parts are used in medical and dental applications and in jewellery or as watch parts.
  - Even copper base alloys and aluminium parts have started series production. The high thermal conductivity of aluminium is the reason to use it for heat sinks.

Process : Metal Powder

- **Heavy metals and tungsten alloys**
  - Heavy metals and alloys such as tungsten, cobalt and nickel based high temperature alloys are also produced by metal injection moulding, as are tungsten carbide-cobalt cemented carbides for cutting tools and wear parts.

Process : Metal Powder

- **Nickel-free alloys**
  - Increasing demand for nickel-free alloys in applications, where parts are in direct contact with human skin or tissue, as harmful allergic reactions could be caused by nickel.
    - Examples are found in the jewellery and watch making industry, as well as in binocular frames, orthodontic brackets, and medical technology.
  - Excellent corrosion resistance often demand high strength. Various alloys have been designed which fulfil the requirements of sintering technology and at the same time provide the material properties required by the application.

Process : Binding Material

Binder in early MIM Process

- Binders used in the original MIM process were **mixtures of a polymer** like polyethylene or polypropylene, a synthetic or natural wax and stearic acid.

- This type of binder were easy to mould, but the removal of the binder required very careful heating in a thermal process lasting 24 or more hours
  - The binder in the parts softened and the risk of distortion was extremely high. Time consuming binder removal process resulted in high processing cost

Process : Binding Material

Polyacetal Binder Systems

- Invention of a binder system based on polyoxymethylene (POM) - significant progress towards a reliable MIM manufacturing process for volume production.
- Good mouldability and excellent shape retention.
- Binder removal done in a gaseous acid environment
  - Highly concentrated nitric/oxalic acid (catalyst in the decomposition of the polymer binder), at a temperature of approximately 120°C (which is below the softening temperature of the binder).
  - Today a large portion of MIM parts are produced according to this patented process.

Process : Debinding

Solvent Debinding

- Most successful binder removal techniques.
- The binder composition includes a constituent that can be dissolved in a liquid at low temperature so that a network of interconnected porosity is formed in the part while immersed in the solvent.
- Acetone is sometimes used as the solvent although water soluble binder compositions are preferred since the handling of aqueous solvents is easier than that of organic solvents.
- The solvent which is contaminated with the binder after debinding is distilled and recycled.
- Although solvent debinding may take longer than catalytic binder removal, the investment and operating costs are lower so that the total processing costs are competitive.

Process : Debinding

Supercritical debinding

- Binder removal technique using supercritical carbon dioxide (CO2)
- Supercritical phenomenon exhibited by gases above a certain combination of temperature and pressure (critical point marks the temperature and pressure where the gas can no longer be brought to the liquid state of aggregation)
- For carbon dioxide the critical temperature is 31°C and the critical pressure is 7.4 MPa. The density of CO2 is approximately 0.5 g/cm^3 (less than in the liquid state but much higher than in the gaseous form)

Process : Debinding

Supercritical debinding

- Supercritical state is somewhere between the liquid and the gaseous state. It is characterised by an extremely low viscosity which allows the molecules to penetrate into the fine pore channels that are created during debinding.

- The processing time in debinding of MIM parts is claimed to be about 3 hours.

Process : Sintering

- Sintering is the same process as that used for traditional die pressed powder metallurgy (PM) parts and can be done in continuous or batch type furnaces integrated into a complete production line.
- Carried out in protective atmospheres or in vacuum at a temperature well below the melting point of the metal.
- The type of sintering process and the sintering conditions are depending on the composition and quantities of the materials to be sintered.

Process : Sintering

- The parts are placed on ceramic trays or in heat resistant boxes while they are in the sintering furnace.
- Unlike die pressed PM compacts, MIM parts must undergo a large shrinkage during sintering which may require higher sintering temperatures and/or longer sintering cycles.
- The continuous binder removal and sintering process allows economical mass production of ferrous metal injection moulded parts.

Metal Powder + Binder

Ready-to-use granules containing powder and binders

Injection Molding

The part is molded. (Green part)

Debinding

The binder is removed. (Brown part)

Sintering

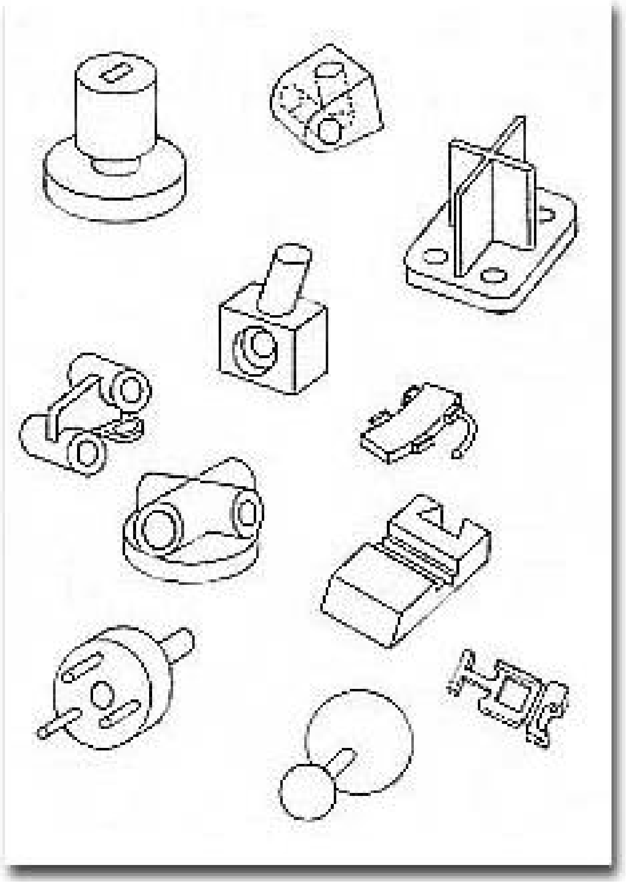
High temperatures give the part its final size and properties. (Sintered part)

Design : Uniform Wall Thickness/Holes

Uniform wall thickness/holes

- Uniform wall thickness is critical in order to avoid:
  - distortion,
  - internal stresses,
  - voids,
  - cracking
  - sink marks.

- Variations in wall thickness also cause variations in **shrinkage** during sintering making dimensional control difficult.

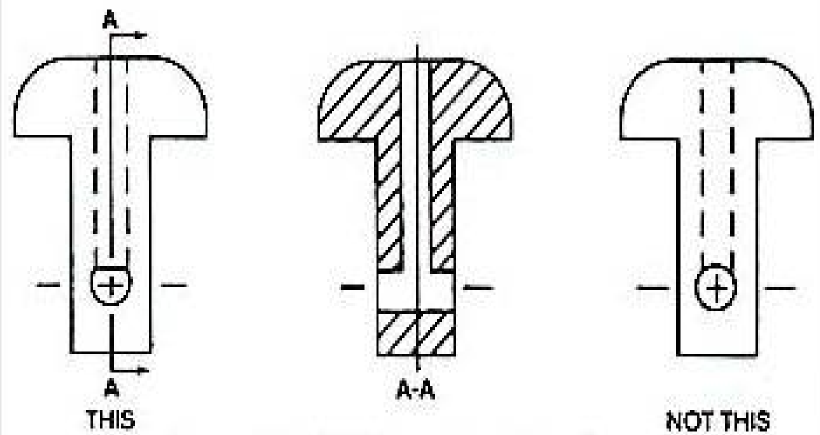


Design : Uniform Wall Thickness/Holes

- One method used to attain uniform wall thickness is **coring**,
  - Reduce cost by reducing material and processing times.
- In some parts coring can easily be achieved by adding holes that are formed by pins protruding into the mould cavity.
- Through holes are easier to mould than blind holes, because the core pin can be supported at both ends.

Design : Uniform Wall Thickness /Holes

- **Blind holes** formed by pins supported at only one end can be off centre due to deflection of the pin by the flow of feedstock into the cavity.
  - Therefore the depth of a blind hole is generally limited to **twice the diameter** of the core pin.
  - Avoid **perpendicular** holes to one another cause special problems of sealing-off or closing-off in the mould.
  - By redesigning one hole to a **'D' shape**, the tooling will function better, be stronger, and minimise flashing.



Make Cross Hole "D" Shaped to Allow Close Off of Tool Members in Mold

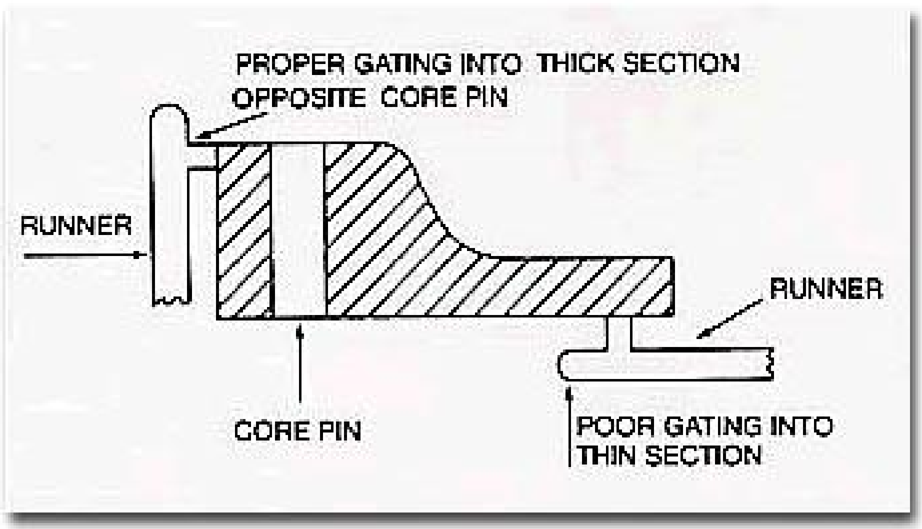
Design : Uniform Wall Thickness/Holes

- **Reinforcing ribs** are another effective way to **improve rigidity and strength** in parts with thin walls.
  - can increase part strength,
  - improve material flow,
  - prevent distortion during processing,
- Negative side of ribs:
  - warpage,
  - sink marks,
  - stress concentrations.
- Ribs should be added to a part design cautiously, and it is often better to wait for an evaluation of the initial tool samples.

Design : Gating

Gating

- **Gate:** Opening where feedstock enters the mould cavity.
- Gate locations should permit the feedstock to **flow from thick to thin** sections as it enters the mould cavity.
- A flow path of **thin to thick**, will cause voids, sink marks, stress concentrations and flow lines on the part surface.



Design : Gating

- Many MIM components are produced using **multiple cavity** tooling, where each cavity must be identical to the others.

- To ensure part reproducibility, the **gate and runner system** to each cavity must be
  - carefully sized and located
  - each cavity will be filled with the identical amount of feedstock (balanced fill rate).

- Since the gate will leave a mark or impression, its **location must be carefully selected** with regard to part function and appearance.

Design : Surface Finish

Surface Finish

- Approximately 0.80 µm,
- Better than most investment castings.
- Profilometer readings may be affected by **residual porosity** and are subject to interpretation.
- The surface finish of MIM parts can be improved by conventional processes such as grinding, lapping or burnishing.

Design : Part Ejection from Mould Cavity

Part Ejection from Mould Cavity

- Draft, or a **slight taper**, may be required for the ejection of parts from the mould cavity. This is particularly true for core pins, and the need increases with the depth of the hole or recess being formed.
- **Draft angle** from **0.5° to 2°** is generally sufficient.
- **Knock-out ejector pins** are usually required for removing parts from the mould, and good design of these pins is critical to minimise flash marking of the parts.

Design : Reducing Stress Concentrations & Threads

Reducing Stress Concentrations

- Avoid **sharp internal corners** and **notches** will cause stress concentrations.
- Thus generous **fillets or radii**,
  - improve feedstock flow
  - assist in the ejection of the part
- Both inside and outside corners should have radii as large as possible, typically **not less than 0.4 to 0.8 mm**.

Threads

- External and internal threads can be **automatically moulded**
  - eliminating the need for mechanical thread-forming operations.
  - Internal threads: tapping should be considered (cost effective) .

Design : Parting Lines and Undercuts

Parting Lines

- Parting lines are formed by the opposing faces of the mould, in the plane where the mould halves are separated to permit removal of the part. With moulds of normal construction this feature is transferred as lines or witness marks onto the surface of the parts

Undercuts

- Undercuts, classified as internal and external are often required for part function.
- Undercuts may increase tooling costs and lengthen cycles, but this is **dependent on the type and location of the undercuts on the part.**
  - *External undercuts*
  - *Internal undercuts (not recommended)*

Design : Tolerences

Tolerances

- MIM processing normally requires a dimensional tolerance of +/- 0.003 mm/mm (+/-0.3%).
- As part size decreases, increasingly tighter tolerances can be achieved.
- Reduction in tolerances is **not directly proportional to decreasing dimensions,** depend on:
  - material,
  - part shape,
  - process requirements.

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Design : Tolerences

- Some **general rules** concerning tolerances in MIM should be noted:
  - tolerances specified **should be no closer than absolutely required** for satisfactory performance
  - close tolerances:
    - should not be specified for parts having major wall thickness variations
    - increased part cost
    - should not be specified across a parting line or for dimensions controlled by movable cores or sliding cams

Design : Size of MIM Parts

Size

- There is, theoretically, **no limit to the maximum size** of part that could be produced, but economic considerations restrict the sizes that are currently viable.

- There are **two important factors** in this connection:
  - The **larger** the part the greater is the proportion of the overall cost (**raw material cost)**.
  - The **thicker** the section the longer the **debinding time**, and thus the higher the cost of that part of the process.

MIM Benefits

- **Design Freedom**
  - Offers design flexibility similar to plastic injection molding.
  - Geometrically complex parts

- **Enhanced Details**
  - Provides intricate features e.g dovetails, slots, undercuts, threads, and complex curved surfaces.
  - Produce cylindrical parts with greater length-to-diameter ratios.

MIM Benefits

- **Reduced Assemblies**
  - Combine two or more simpler shapes into a single, more complex component
  - Minimize assembly costs.
- **Reduced Waste/Machining**
  - Provide net shape components
  - Eliminates secondary machining operations.
- **Improved Properties**
  - Parts are typically 95% to 98% dense, approaching wrought material properties.
  - Greater strength, better corrosion resistance, and improved magnetic properties than conventional powder metallurgy processes

Comparison of parts manufacturing processes in terms of shaping capabilities

Property	Investment casting	MIM
Min. bore diameter	2mm	0.4mm
Max. depth of a 2mm dia blind hole	2mm	20mm
Min. wall thickness	2mm	<1mm
Max. wal thickness	unlimited	5mm
Tolerance at 14mm dimension	+/- 0.2mm	+-0.06mm
Surface roughness Ra	5µm	4µm

MIM Benefits

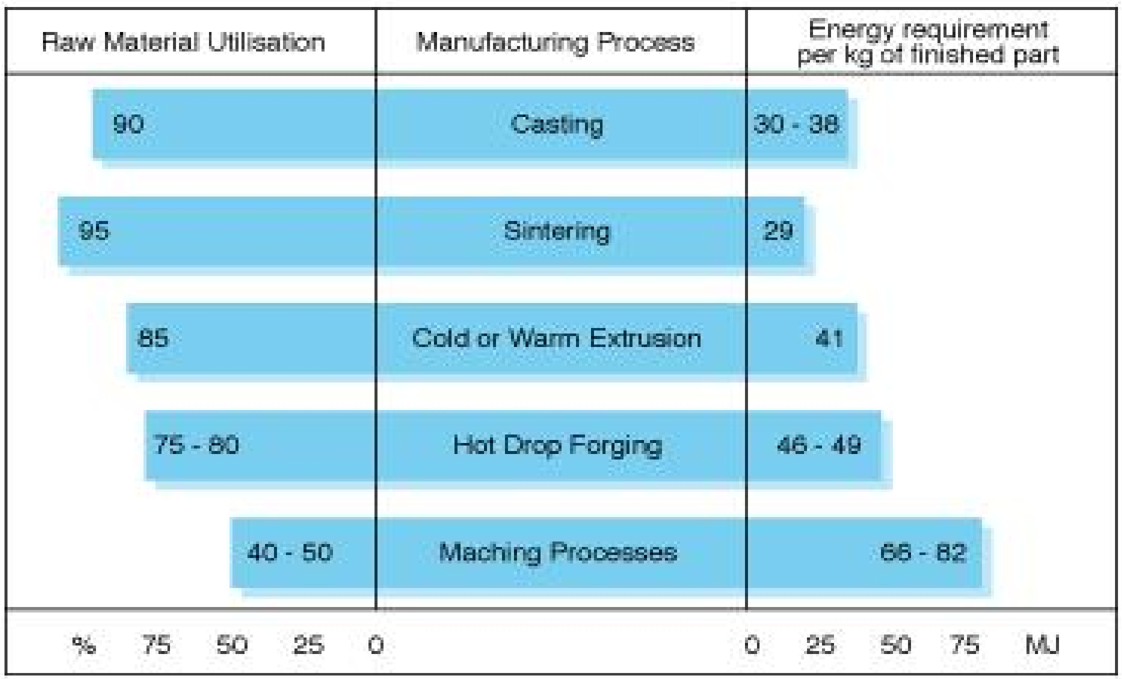
- **Cost Saving**
  - **BETTER MATERIAL UTILISATION WITH CLOSE DIMENSIONAL TOLERANCES**.
    - Conventional metal forming or shaping processes, against which MIM/PM competes, generally involve significant machining operations from bar stock or from forged or cast blanks.
    - These machining operations can be costly and are wasteful of material and energy.
    - material utilisation in excess of 95% can be achieved with close dimensional tolerances.

MIM Benefits

- **Cost Saving**
  - **ENERGY SAVINGS**.
    - The energy savings alone contribute significantly to the economic advantage offered by MIM/PM.
    - An example is given below for a notch segment used in a truck transmission, where MIM/PM consumes only around 43% of the energy compared with forging and machining and the number of process steps has been greatly reduced.

MIM Benefits

- **Cost Saving**
  - **BETTER MATERIAL UTILISATION WITH CLOSE DIMENSIONAL TOLERANCES AND LESS ENERGY REQUIRED**



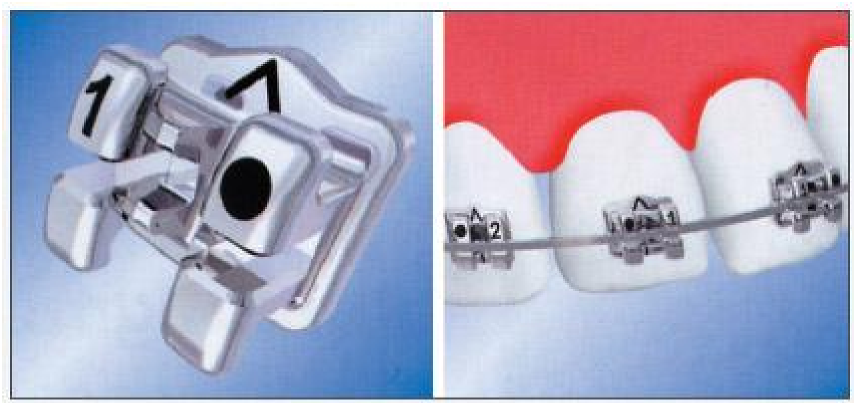
Raw material utilisation and energy requirements of various manufacturing processes

MIM Limitations

- **Size** – The economical part size is typically limited to **less than 100 grams** due to the cost of the fine metal powders used for MIM parts.
- **Section Thickness** – The maximum section thickness is generally kept to **less than 0.25 inch** to effectively remove the thermoplastic binder from the part without damage, and to control distortion during sintering
- **Tolerances** – Typically +/- 0.5 percent, down to +/- 0.001 inch (0.025 mm) for very small dimensions. Tighter tolerances require secondary machining or grinding operations.
- **Production Volume** – Tooling costs generally limit the economic annual production **volume to greater than 10,000 parts** (with exceptions for very expensive parts).

Applications

- Many objects we encounter in everyday life contain metal injection moulded parts ranging from medical products, firearms to automotive parts and etc.



Orthodontic brackets

Watch components

Application: Hydraulic coupling

This angular part composed of 316L is a hydraulic coupling for small cylinders in a convertible. This coupling part employed in hydraulic systems has been produced up to now by soldering the two end pieces onto a prefabricated tube and then bending it.

Using this technology it is possible to achieve the final shape in one forming step and to lower the overall fitting height markedly. Soldering and turning of the end pieces are also rendered superfluous.

Application: Combustion chamber

In the case of this combustion chamber for auxiliary heating systems made from austenite 316LG. The technology has substituted precision casting as the manufacturing process. Apart from distinctly lower-cost production it was also possible in this way to replicate engineering details which were not possible in precision casting. Fine structures, cross holes and blind holes could be very effectively formed.

Application: Consumer generating reliability

Cogs

These small cogs were manufactured from an extremely fine grained pure iron powder and nickel-plated after sintering.

Application: Mechanical assuring safety

Locking disk

The locking disk made of 17-4PH temperable stainless steel is a functional part of a lock mechanism designed to prevent unauthorized opening of machine tools.
The part is exposed to high mechanical loads, especially on the outer webs. It is possible to make the disk very thin without any need for additional mechanical operations.

Application: Control valve

This component was earlier composed of four separately manufactured segments which had to be positioned and then soldered together.
Using MIM the component can be produced as compact finished part in essentially three process steps.
The material used is 316L austenitic stainless steel, which offers superior strength and corrosion resistance to that of chrome-plated brass.

Conclusion

- Many objects we encounter in everyday life contain metal injection moulded parts.
- MIM has overtaken investment casting or precision casting with benefits of better precision, lower cost and greater opportunity for miniaturisation.
- Properties equivalent to wrought can be achieved by MIM.
- Rapid expansion of MIM possible through greater awareness of advantages.