Lecture 5: Casting and metal Injection Molding

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Learning objectives

- Introduction / *'From bronze age axes to car engine'* : a long history…
- Casting processes / Description
  - Sand casting
  - Lost-wax casting ('cire perdue')
  - Die casting
  - Metal-injection-molding
- Physics and metallurgy of casting
- Micro-casting

In this lecture, we will review important manufacturing processes, called 'casting'.

It is quite unique from many aspects. Particularly remarkable and, as we will see in the follow-up slides, casting is one of the oldest known process from human-being, yet still very much in used in modern days.

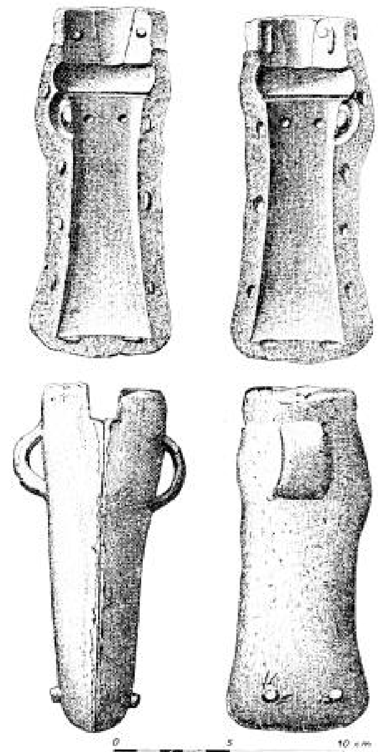
Casting encompasses multiple implementations. In this course, we will focus mainly on sand casting, low-wax casting ('cire perdue') and die-casting processes that are the three most common casting processes.

We will also discuss a variation of these processes, dedicated to metals, that is called 'Metal-Injection-Molding'.

Casting: from the Bronze age...

(from ~ – 3000 BC to ~ - 1000 BC)

Hénon, Côte d'Armor, Brittany (Bronze age)



Mold for a bronze age Axe
(Cachette d'Azay-le-rideau)
From: Cordier Gérard. Quelques moules de l'Age du Bronze provenant de la Touraine et du Berry. In: Bulletin de la Société préhistorique de France, tome 59, n°11-12, 1962. pp. 838-849)
Metal: Bronze (Copper / 85.2%, Tin / 10.2%, Antimony / 2.8%, Lead / 1.8 %)

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Casting is probably known since at least -3000 BC in Mesopotamia. (If you would like to read more about the topic, here is a first known example of the lost-wax molding method in history: https://lejournal.cnrs.fr/videos/le-mystere-de-lamulette.)

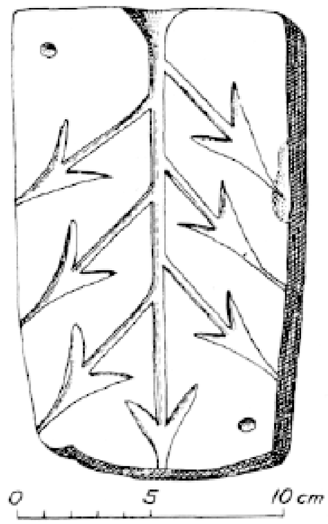
Here are some examples of cast axes from the bronze age, found in Brittany and in the Loire valley.

The left image shows examples of 'large-scale' production of bronze axes. The right image shows an example of the two parts of a metal mold. This metal mold was probably use to replicate the axis. First some kind of wax - most likely bee wax, was poured inside the mold to make a replica of the axes.

After demolding and solidification, the replica was probably used for defining the cavity of a clay mold. The clay was then solidified (probably through firing) and then used to pour liquid metal in. Once solidified, the clay was broken to free the axe from the mold.

The process would be repeated for as many axes as needed.

Casting: from the bronze age...



'Moules pour sept pointes à fondre d'un jet' - Corcellettes, rive ouest du Lac de Neuchâtel / Grandson
(From B. Van Muyden and A. Colomb, 'Musée cantonal Vaudois: antiquités lacustres', Album Lausanne, 1896)

Final bronze age (1550-1200 BC).

Another example of bronze age mold, this time from Grandson, nearby Neuchâtel. This mold was probably used to produce seven arrow-heads at once. This time, the mold was directly made of stone.

Note the two pins used for positioning and aligning the two parts of the mold.

Casting: a long history...

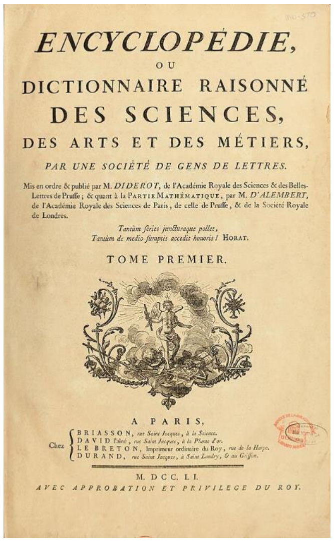
Benvenuto Cellini : Perseus (~ 1545)

Casting has then been used throughout centuries, being gradually perfected.

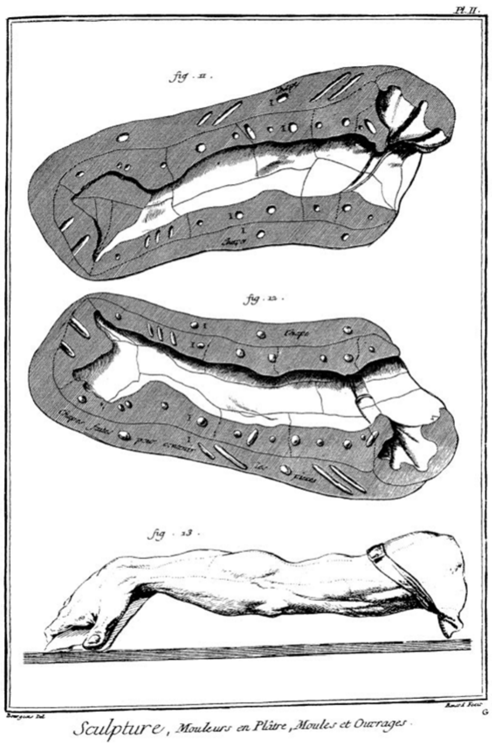
The technique has been for instance to cast statue, such as the Perseus above, realized by Benvenuto Cellini, a Italian renaissance sculptor from Florence. This statue illustrates the level of precision and mastering of the technique reached at that time.

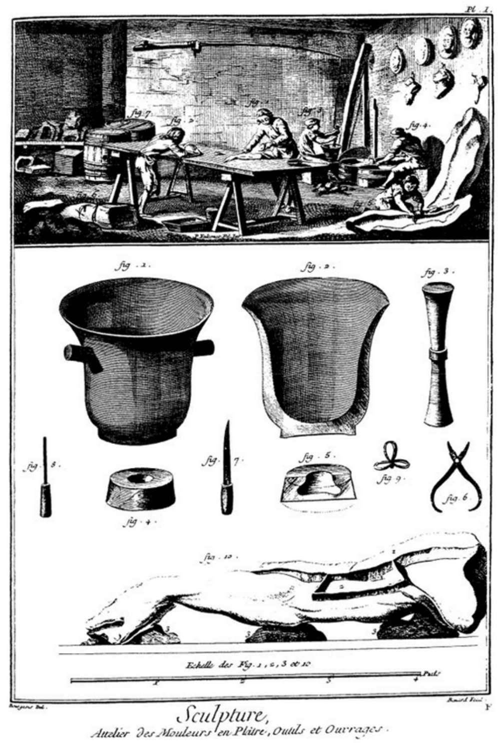
If you would like to explore the history of the topic, here are two interesting links to article explaining the method.
https://dsao.chateaudespeyran.fr/decouvrir-la-sculpture/les-techniques/le-moulage/ (in French)
https://www.metallurgicpark.net/techniques-moulage-coulage-creation-de-statues/

Casting: a long history…



Encyclopédie de Diderot-d'Alembert (1757)





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Example of casting methods used by sculptor described in the first Encyclopedia from Diderot-d'Alembert in 1757.

Although casting of metals is known for millennia, it remains a key process for producing complex 3D parts out of metals, very much in used still today.

Casting processes in modern days

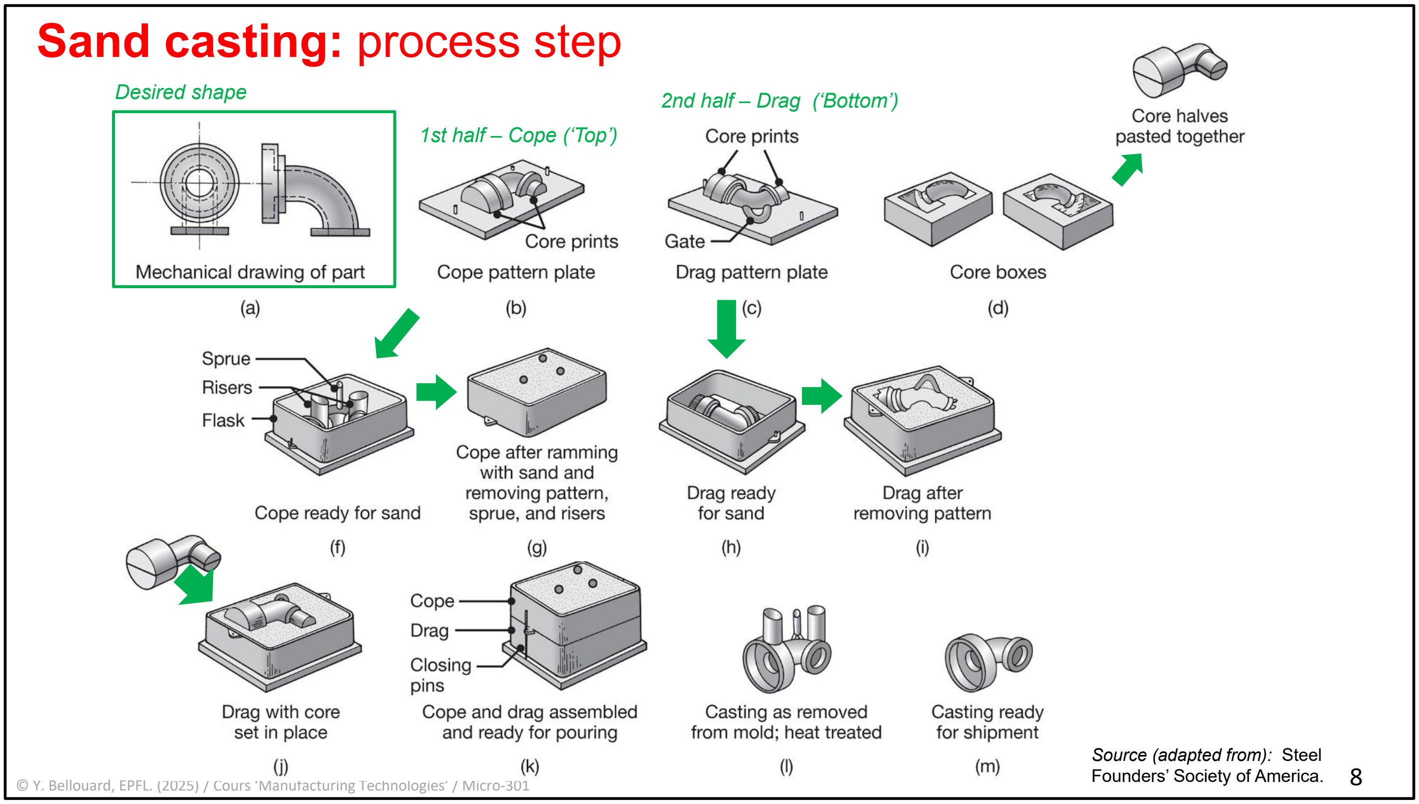
- Sand casting
- Lost-wax casting (‘cire perdue’)
- Die casting
- Metal injection molding

There are four main casting processes that are listed above and that are commonly used.

In the sequel, we will describe each of these processes, their working principles and what these processes have in common as well as their differences.

In the second part, we take a closer look at the material engineering and at the physics of the casting.

In parallel of these notes, we encourage you to have a look at the videos and animations posted on the Moodle.



Let us consider the case of a curved metal pipe as shown in **a**. This metal pipe is manufactured using sand casting.

The first step is to define a plane where the part can be divided into volumes, so that two sides of a mold can be defined. The volume defined by the two parts of molds are such that once put together, they form the final part volume. The top part of the mold is commonly called '*Cope*', while the bottom part is named the '*Drag*'.

A key feature of this example is that it is hollow. Hence, the metal need to be poured in so that at the end, the center of the pipe remains empty of metal.

To achieve a molded hollow structure, a '*core*' is added.

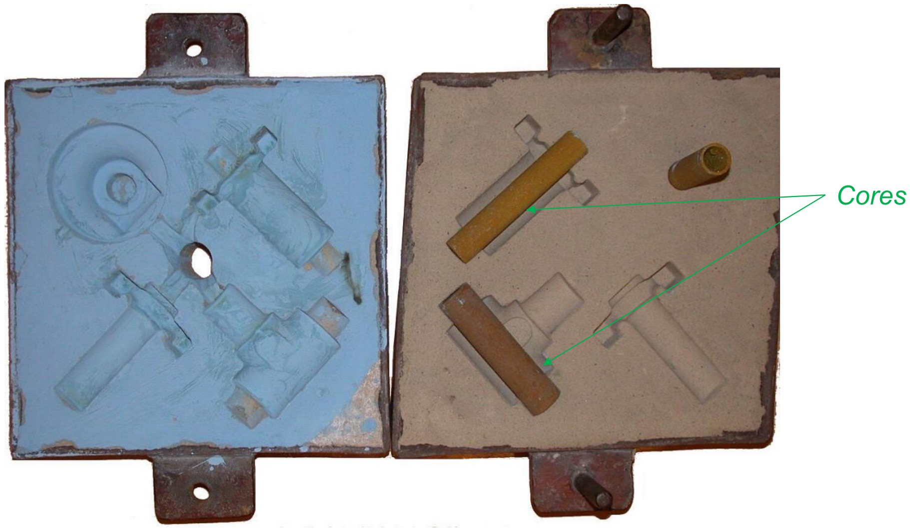
The core itself can be manufactured also by molding (as shown in d) or by other means. It is a plein part that can be made out of different materials, but usually out of denser sand. The cope and the core prints are put in a container. Elements (f) (sort of chimneys and volumes that are used to pour the metal in and vent gases as well as to help the solidification) are added to the cope. The detailed functions of these elements will be discussed in the follow-up slides. Sand is then poured in both containers and the prints are removed, leaving an empty volume in the sand. The core is then place in the cope and the two parts of the molds are put together (k) to seal the mold. At this point, metal is poured in the mold. After solidification, the sand is removed along with the core. The last step is to cut out the added elements (sprue and vents) (steps, l to m).

Sand casting

- Illustrative interesting didactical videos:
  - Car engine block fabrication: https://youtu.be/211Xkut0VGI
  - Car engine (BMW) Industry: https://youtu.be/N2hYTdrzujI

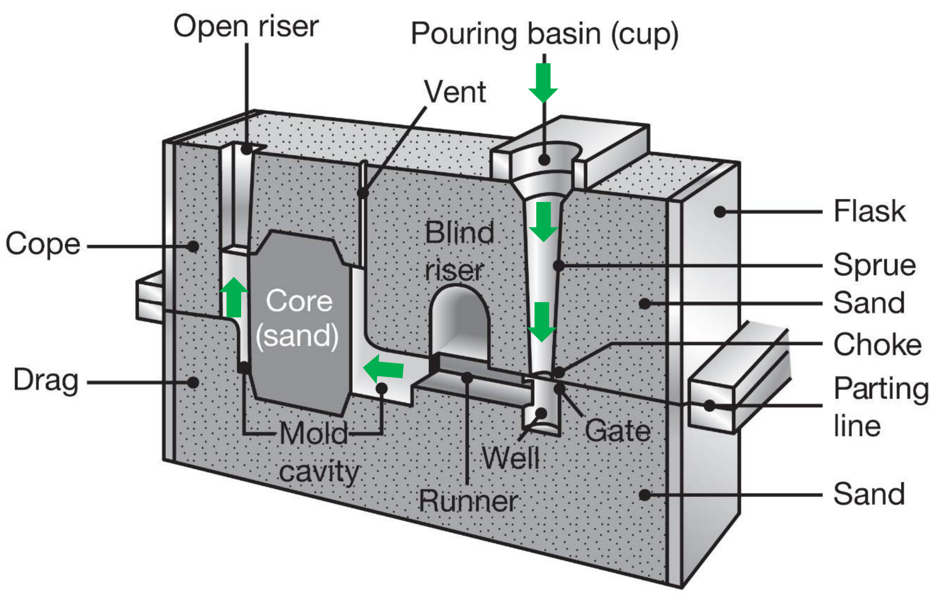
Sand casting molding is a process used in the car industry to produce engine parts as illustrated in these two videos.

Illustration



An illustration of two part of mold made in sand. Two cores, i.e., inserts to realize hollow structure, are visible.

Sand casting mold: a typical configuration



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A typical configuration of a sand-casting mold is shown above, with an example of the various components that one may find, such as:

- The *cope* is the name given to the top part of the part, while the *drag* is the name of the bottom part.
- The *pouring basin* where the hot metal is poured in.
- The *sprue* guides the hot met towards the mold cavity through the *runner*.
- A well is added to prevent the metal from solidifying as it moves into the *runner*.
- A *core* is added here to form a hollow structure.
- A *riser* that will be filled up too, and that is used to feed the mold during metal solidification and to prevent the metal at the entrance to solidify too rapidly, e.g., before the rest of the mold is full.
- The *open riser* is where the metal will exit the mold and indicates when it is full.
- Although sand is porous, a vent can be added to help the gas getting out of the mold and to ensure uniform filling.

The trajectory of the hot metal is illustrated with green arrows.

Why 'sand'?

(Discussion in class)

1. **Refractory** material (low conductivity)
2. **Permeable to gas**
3. Thermally **stable**
4. Do not degrade when the metal shrink
5. Can be removed easily
6. Reusable

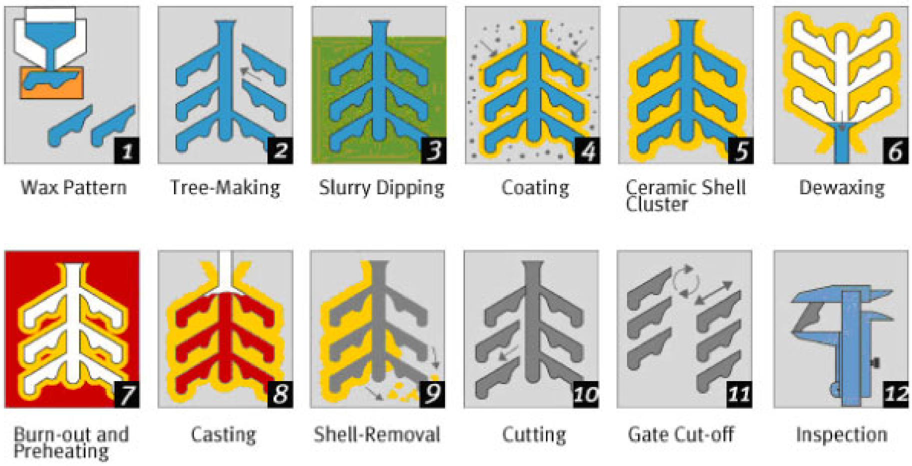
- 'Green sand casting'
  - Use of a mix of natural sand, clay and water
  - Compacted

There are multiple reasons why sand is used. In addition to being widely available in small grains, which makes it easy to fill in preforms and to remove once the casted metal has solidified, it has a low thermal conductivity and is particularly stable even at high temperature.

Once the hot metal is poured in the mold, the sand does not degrade, at least up to elevated temperature in the range of 1500 C. It can also be reused and densely compacted.

Lost-wax casting (‘Cire perdue’)

- Also called ‘Investment casting’



Working principle: https://youtu.be/33p0Nih6YkY
La même... En Français: https://youtu.be/wJJMc9NUPO4

Let us now discuss the lost-wax casting - also known as ‘cire perdue’, another principle for casting metal parts. It is usually used for producing multiple, similar parts at once.

The principle there is to first form the inner parts of the molds by assembling wax patterns around a column to form a tree (1-2). The wax pattern is then dip into a slurry containing ceramics particles (3) that will agglomerate in a dense coating around the wax model (4). Once fired, this coating becomes a dense and solid ceramic shell around the wax preform (5). The wax is then removed by heating-up (6-7), so that only the outer-shape is left.

At this stage, metal is poured in and fill-up the entire mold (8). Once solidified, the shell around the metal is removed (9) and the individual parts are cut out from the ‘three’ (10-11). The last steps involve inspection (12) or other post-treatment steps.

Other methods: centrifugal casting

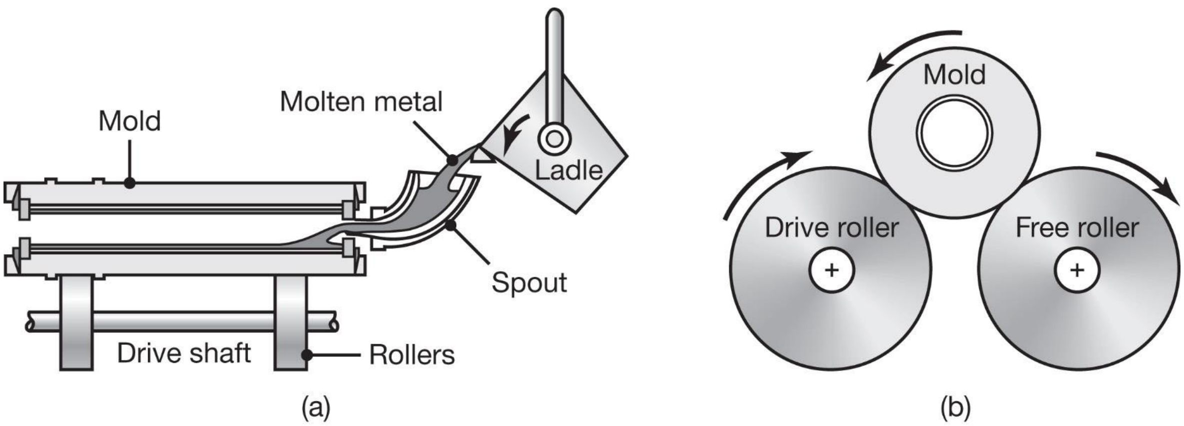


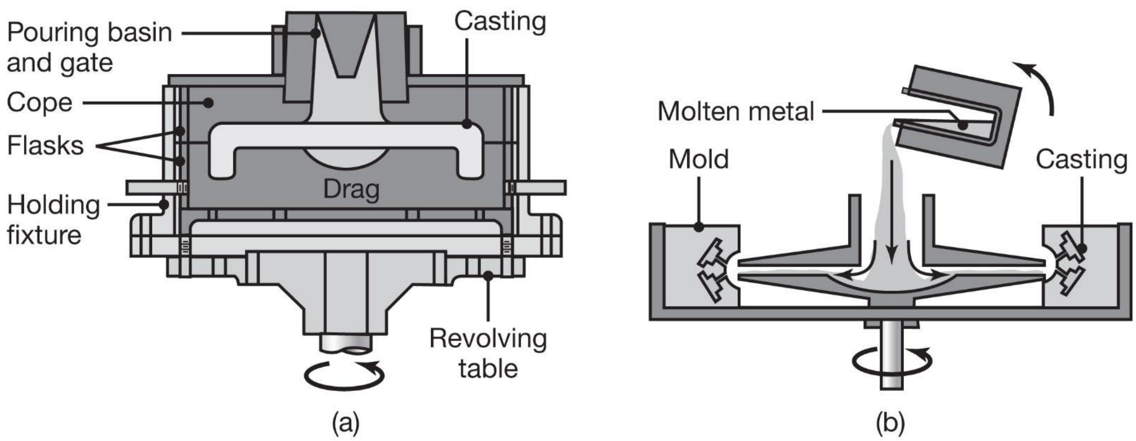
Illustration (MetalTek Int.): https://youtu.be/o4vkUHb91H0

(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

There are several additional casting methods that have been developed for specific cases, like for instance the centrifugal casting that uses centrifugal forces to from elongated pipes. The mold consist itself on a pipe that is rotated between two rollers.

The metal first solidified on the outer surface. The solidification front then moves inward as the metal cools down, creating a particular structure due to the directional solidification that occurs. Note that the concept of directional solidification will be explained in follow-up slides. Furthermore and due to the centrifugal forces, the denser material concentrates on the outside of the pipe, while impurities are found on the inside, making them easy to remove. This phenomena makes casting products using this method particularly dense and resistant.

Semi-centrifugal process



(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

Semi-centrifugal casting as shown in the left image is used to produce parts with cylindrical symmetry and for which the center part can be removed. The advantage of this process is that the centrifugal force helps pushing the metal to fill the mold uniformly, ensuring that the denser part of the metal is found on the edge.

The variant on the right as the same purpose but this time to produce multiple parts distributed around the circumference of a rotating mold. One advantage is that, thanks to the active force that pushes through, the metal is poured under pressure and hence, can fill cavities with small features.

Die casting

- Use of a metal die
- Injection of metal into the die

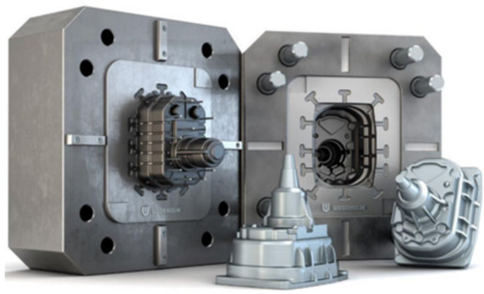


Photo credit: Mannat Engineering Works

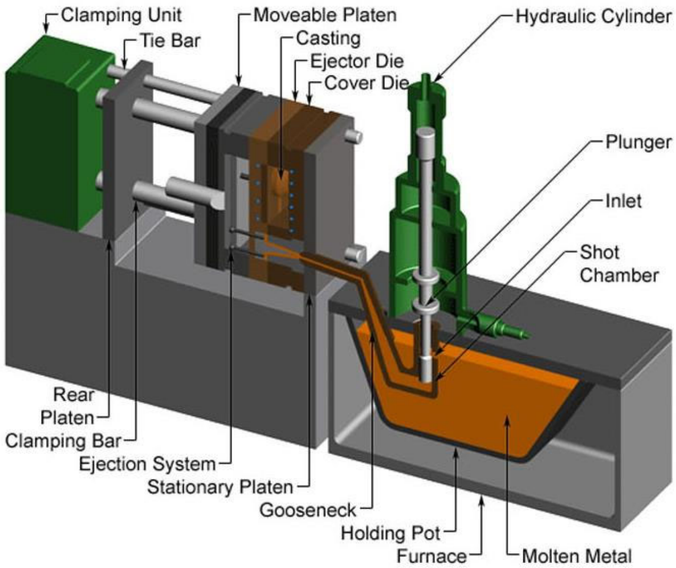
Unlike sand casting, die casting makes use of a die as a mold. The mold is this time reused multiple times making the process a capable high-throughput process suitable for high-volume productions.

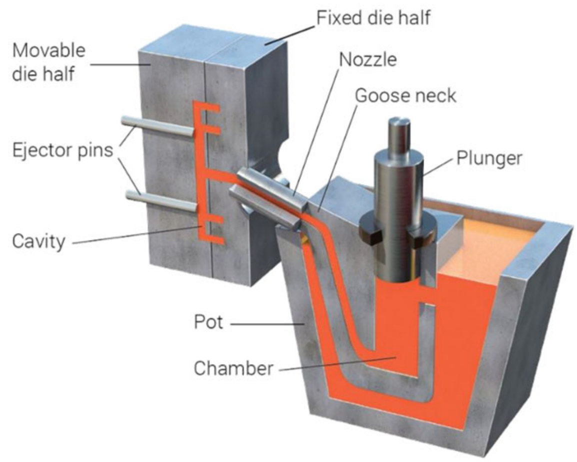
The mold itself is made of metal and is usually manufactured by electro-discharge machining (see lecture on 'unconventional machining' processes). The mold can be quite complex and sophisticated as illustrated above.

The molds themselves are usually expensive to manufacture. They can cost easily a few tens of kCHF, but as we will see, the cost can be justified for high level productions (above >10k parts).

Before examining the process requirements and its constraints, let us first describe its working principle.

Die casting





Source:www.engineeringclicks.com

- Various principles for dispensing the hot metal

(illustration: A&B Die Casting) 17

In die-casting, this time the mold is made of die that is reused multiple time. Just like the other molds seen before, the mold is made of two parts, but this time out of metal. As solidification occurs rapidly (the metal cools down rapidly), infiltration is done rapidly using a plunger that pushes the metal through a syringe-like nozzle. To pull the part out of the mold after solidification, ejectors pins are used.

This casting method are used for high-throughput production and is more suited for small parts. The dies are expensive as they require high-quality finishing. Such dies are typically made by electro-discharge machining (or in short, EDM), a process that we will review later in this course.

One of the difficulties is to prevent the mold from reacting with the metals being poured in, and because of this limitation, the process is limited to non-ferrous metals.

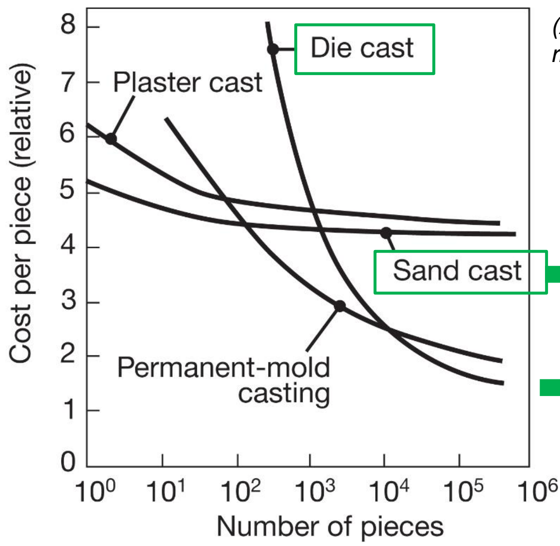
Comparison

Process	Advantages	Limitations
Sand	Almost any metal can be cast; no limit to size, shape or weight; low tooling cost	Some finishing required; somewhat coarse finish; wide tolerances
Shell mold	Good dimensional accuracy and surface finish; high production rate	Part size limited; expensive patterns and equipment required
Expendable pattern	Most metals cast with no limit to size; complex shapes	Patterns have low strength and can be costly for low quantities
Plaster mold	Intricate shapes; good dimensional accuracy and finish; low porosity	Limited to nonferrous metals; limited size and volume of production; mold making time relatively long
Ceramic mold	Intricate shapes; close tolerance parts; good surface finish	Limited size
Investment	Intricate shapes; excellent surface finish and accuracy; almost any metal cast	Part size limited; expensive patterns, molds, and labor
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate	High mold cost; limited shape and intricacy; not suitable for high-melting-point metals
Die	Excellent dimensional accuracy and surface finish; high production rate	Die cost is high; part size limited; usually limited to nonferrous metals; long lead time
Centrifugal	Large cylindrical parts with good quality; high production rate	Equipment is expensive; part shape limited

(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

The table above offers a comparison between various molding methods. It is not meant to be exhaustive, but just to provide some general information.

Cost comparison between processes



(Assuming the same part can be made using all these processes)

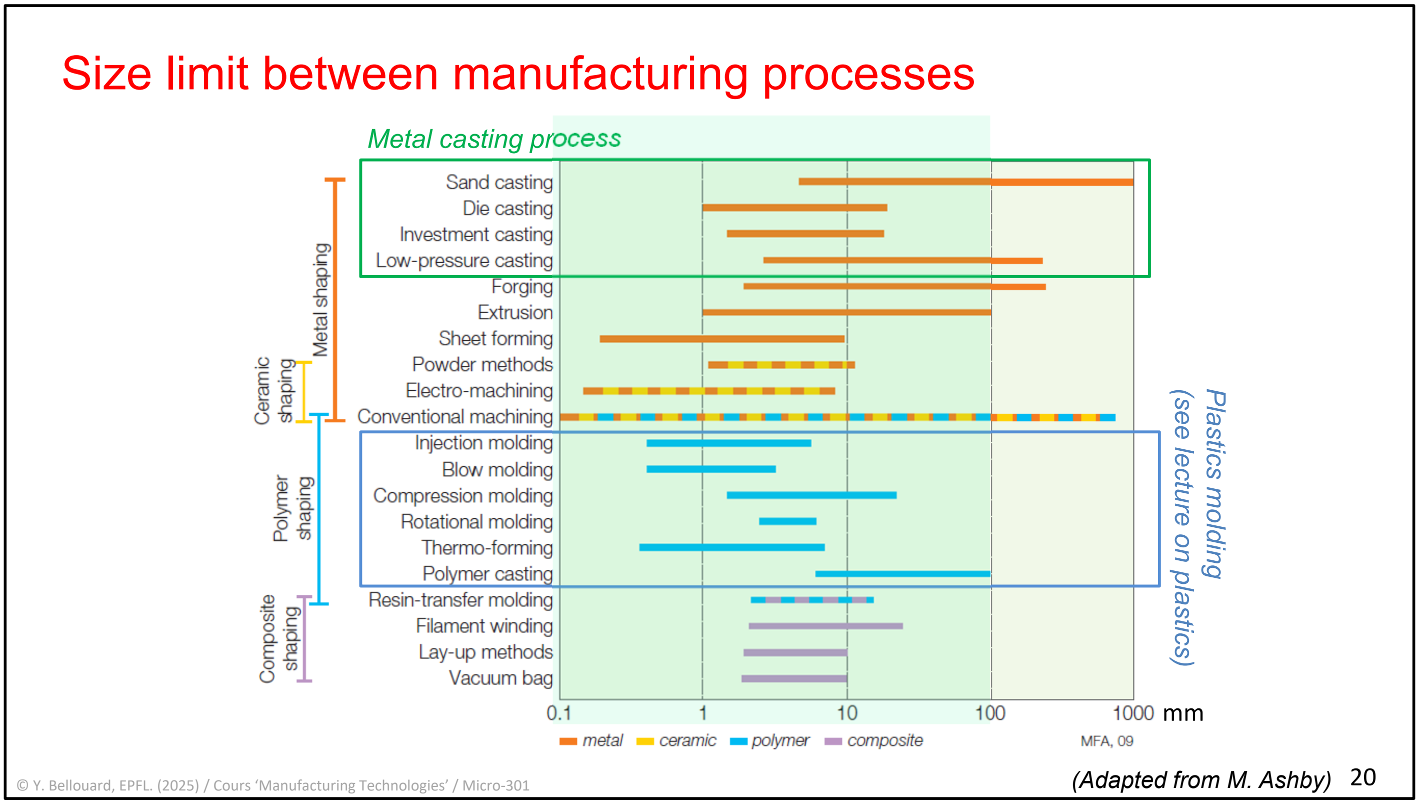
Low-tooling cost, limited effect of the number of parts on the cost

High-tool cost (typ. mold price is >20kCHF), only economically viable if the number of parts is sufficiently high

(source: North American Die Casting Association.)

At this point, it is interesting to compare the cost of parts made with sand casting versus the same parts made by die casting. While the parts are the same at the end, the production cost will depend on the number of parts to be produced.

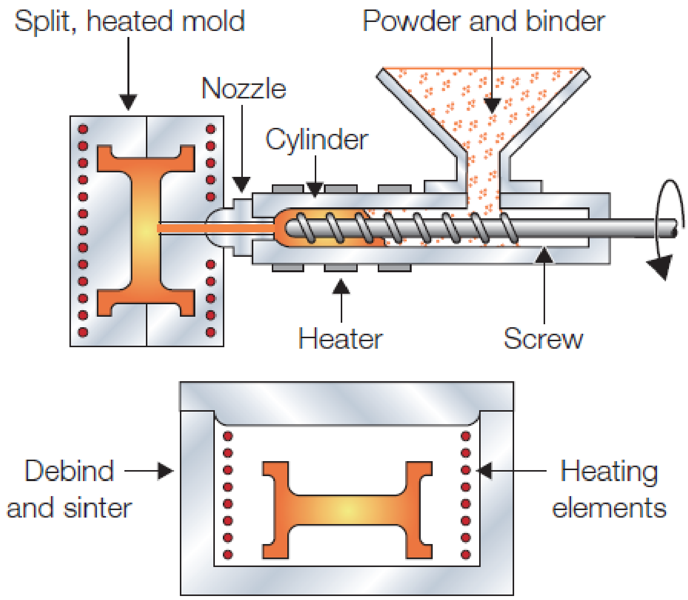
Sand casting has a low tooling cost compared to die-casting. Die-casting becomes economical only if the number of parts typically reaches the thousands.



The graph above gives a general comparison between part sizes and relevant casting processes.

While sand casting is generally applied to medium size to large scape parts – like engines, die-casting and lost-wax casting (also called 'investment casting') are more suitable from smaller scale object not exceeding a few centimeters.

Metal injection Molding



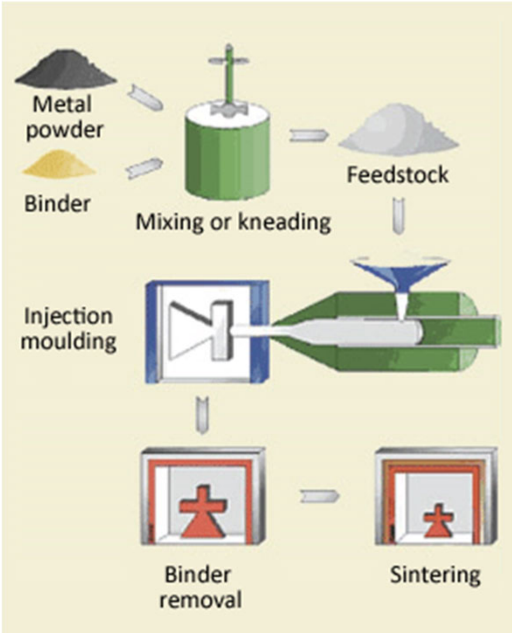
(source Ashby)

Working principle explained:
https://youtu.be/MmLYj3GZsx8

While it is adapted for large scale production of parts, die-casting has several limitations on the possible choice of materials.

A more versatile process is the metal injection molding. There, the principle is to mix principles from powder metallurgy with methods from plastic injection molding.

Metal injection molding



- **Step 1:** Preparing the feed stock
  - Metal powder
  - Thermoplastic binder
- **Step 2:** Injection molding
- **Step 3:** Binder removal
  - Catalytic debinding /Nitric and Oxalic acids @ 120 deg C or Solvent debinding
  - Network of pores
- **Step 4:** Sintering
  - Typ. shrinkage: 15 to 20 %
- **Step 5:** Optional post-processing steps (ex. Hot Isostatic Pressing)

Basic principle of a metal injection molding process (Source: Pim-International) - Illustrative video: https://youtu.be/MmLYj3GZsx8

The figure above shows an overview of a metal injection molding process.

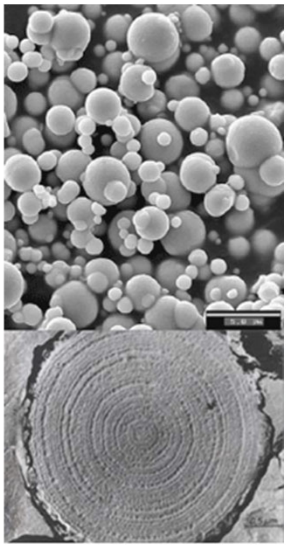
The process starts from a feedstock that is made of mixture of metal powder and a binder made of plastic particles. The mixture is then poured into an injection molding machine that pushes it through a mold.

However, contrary to die-casting, the injection is done at a much lower temperature, the temperature for which the binder melts. In essence the binder is used to 'carry' the metal particles inside the mold.

Once demolded, the part that is made of a composite structure of plastics and metals is freed of its binder by dissolving it. The final step is the sintering process. During this final step, the pores left by the binder after removal are closed and a compact and dense metal part is obtained.

During sintering, consequently to the sealing of pores, the part shrinks by about 15 to 20 % of its volume.

Powders production



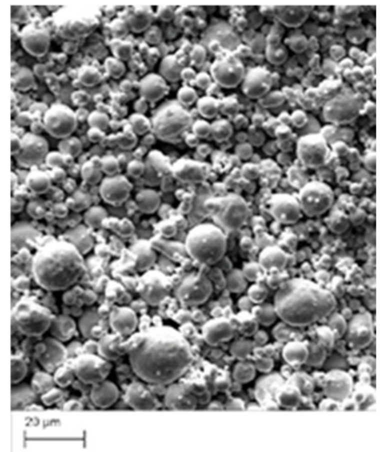
< Carbonyl iron and nickel powders

Powders are mixed with elemental or master alloy powders to achieve the desired alloy composition.

Carbonyl iron powder (SEM, top, with scale showing 5µm) and cross-section of a particle (Image BASF, Germany)

Water and gas atomized powders >

Used essentially for alloys. (Image Sandvik Osprey, UK)



Above are examples of metal powders used in MIM processes.

Binder functions and requirements

- To be able to incorporate a **high volume of fine metal** or **ceramic powders**, typically **60%** by volume
- Form a coherent mass that can be plasticized, and **injection molded at elevated temperature**
- Allow removal of the main binder constituent in a reasonably short time and environmentally friendly process
- Still provide enough strength after debinding by means of the 'backbone binder'
- Be supplied in **a regular granular form** that can easily be fed into an injection molding machine

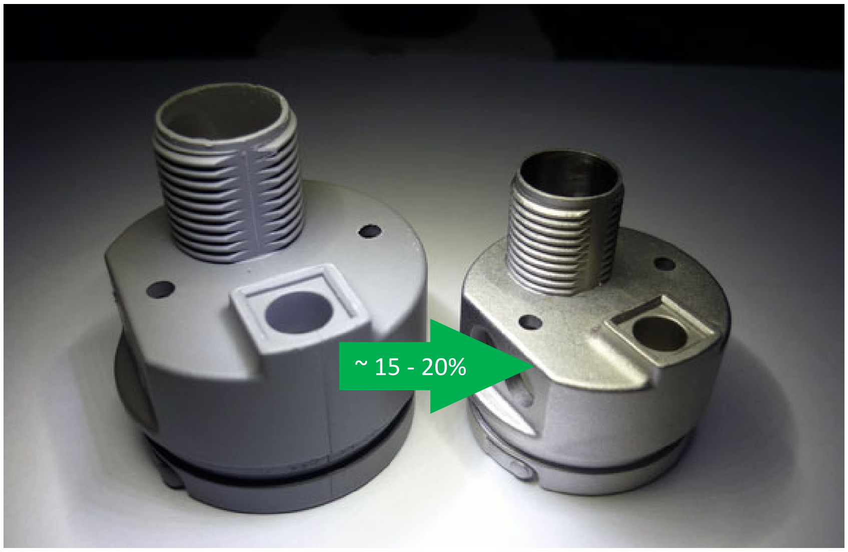
The binder has multiple functions and requirements.

Its first task is to be able to incorporate a high volume of fine metal (or ceramic) powders, which typically represent up to 60% of the volume. It has to form a coherent composite mass that can be injected at elevated temperature (yet, much lower than the melting temperature of the metal used).

The binder should also be so that it can be removed easily by thermo-chemical means, while still having enough strength to hold the part together during processing.

Finally, it is supplied in a regular granular form, so that it can be easily mixed with the metal particles and ultimately be injected in the molding machine.

Illustration of the volume shrinkage occurring during debinding



Metal Injection Molded housing cover made from 316L stainless steel (sensor casing). Before and after sintering. (source PIM International Vol.4 No.1, March 2010)

An image that illustrates the shrinking process occurring after de-binding and sintering. The composite part is shown on the left and the final part on the right.

The image also shows how complex MIM parts can be. Note also, the parting line of the mold in the middle.

Examples of part produced by MIM

MIM knee implant parts made from Ti6Al4V
(Maetta Sciences Inc., Canada.)
Post-treatments: bead blasting, electropolishing and anodizing

17-4 PH stainless steel articulation gear manufactured by Parmatech Inc, USA. (Image Courtesy MPIF, USA)

BMW engines, **metal Injection molded rocker arms** produced by Schunk Sintermetalltechnik GmbH , Germany – Alloy: hardenable 50NiCrMo2.2 steel powder alloy

With the progress made in developing the process, MIM has gained considerable importance in manufacturing.

The images above illustrate examples of parts made using this process, from Titanium-medical devices to engine parts.

Examples of part produced by MIM

Apple connector. (at peak production: 10 Millions of parts per week !)

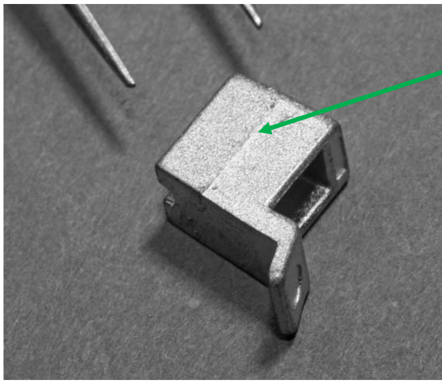
Seat belt component for airplanes (image: MimEcrisa SA, Spain)
m = 90 g / Fe7Ni0.6C steel alloy
UTS (after heat treatment) > 1200 MPa

Swatch Irony (stainless-steel MIM cases).

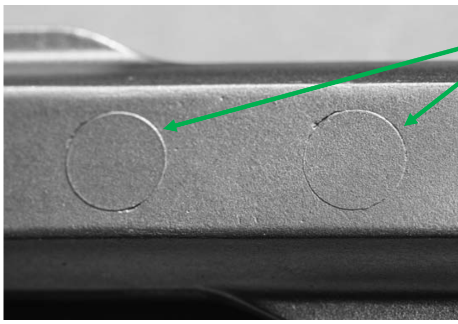
A few more examples of MIM parts. A dramatic example is the Apple connector ('old style') that was produced by this method. It shows the high-throughput capabilities (up to 10 millions / week at some point) of metal-injection-molding.

The two other examples show complex three-D parts with intricated features and the first use in the context of watch manufacturing.

Illustrations



Parting line blemish on a MIM component showing where the two halves of a tool come together.



Typical ejector pin marks shown on a MIM component

Tab gate blemish along parting line on a MIM component.

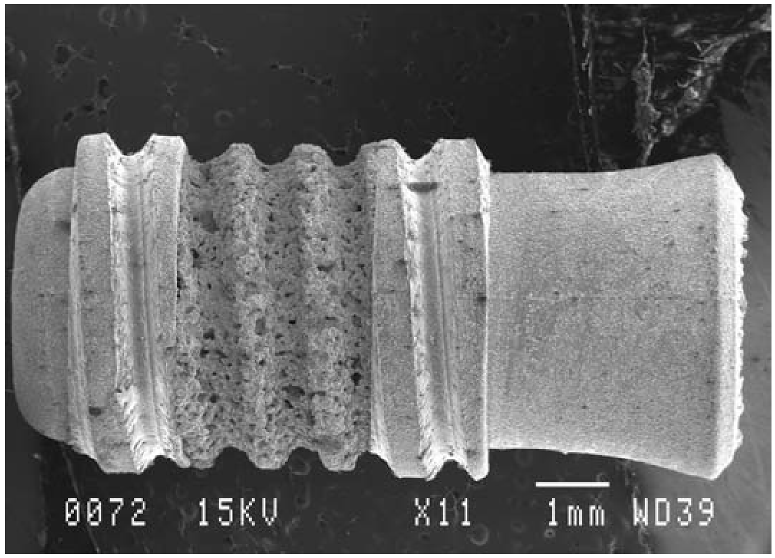
The images above illustrate typical prints left after molding. The parting line is the line revealing where the separation between the two parts of the mold was.

These prints offer clues to identify a molding process among other manufacturing methods.

Other traces from the process are revealed form the tab gate from where the material was poured in and the ejector pin traces.

Note that such prints can also be found for parts that are die-casted.

Examples



Titanium dental implant formed by MIM with an intentional porous region for bone ingrowth (book: Handbook of metal injection molding photograph courtesy of Eric Baril).

An example of a titanium dental implant as seen in an electronic microscope. Part of the implant is left intentionally porous to stimulate bone ingrowth.

Comparison with other processing techniques (indicative)

Metal injection molding — 3D printing — Reference

Attribute	MIM	Powder metallurgy	Casting	Machining
Component size (g)	0.030–300	0.1–10 000	1 +	0.1 +
Wall thickness range (mm)	0.025*–15	2 +	5 +	0.1 +
Percent theoretical density (%)	95–100	85–90	94–99	100
Percent theoretical strength (%)	95–100	75–85	94–97	100
Surface finish (μm)	0.3–1	2	3	0.4–2
Production volume	2000 +	2000 +	500 +	1 +

*Features this small could have distortion.

(source: Handbook of injection molding)

The table compares the MIM process with other competitive manufacturing methods.

MIM processes are capable of higher resolution with smaller feature sizes and surface finish quality. The part density and strength are close to what is normally obtained by conventional machining.

Pros & Cons

- **Simplified** the machining of complex parts (reduced number of operations)
- **Suited for high volume production** (> typ. over 20'000 parts to millions of parts)
- Relative **high raw materials cost** => acceptable for parts where the material cost is not the main manufacturing cost (smaller size parts)
- **Denser** than part produced by powder metallurgy (but less than conventional machining)
- Surface finish comparable to conventional machining
- Part volume shrinkage to consider (15 to 20%)
- Well adapted to small parts

MIM process have several advantages that are listed above.

Like die-casting, it is well adapted for large scale volume production, but not for small volume due to the tooling cost and the relatively higher cost of raw materials.

Compare to other molding processes, it has the disadvantage that a volume reduction is observed after sintering and as to be taken into account during the mold design phase.

MIM specs (indicative)

Attribute	Minimum	Typical	Maximum
Component mass (g)	0.030	10–15	300
Max. dimension (mm)	2 (0.08 in)	25 (1 in)	150 (6 in)
Min. wall thickness (mm)	0.025 (0.001 in)*	5 (0.2 in)	15 (0.6 in)
Tolerance (%)	0.2%	0.5%	1%
Density	93%	98%	100%
Production quantity	1000	100 000	100 000 000

*Features this small could have distortion.

(source: Handbook of injection molding)

The table above shows typical MIM specs. It is essentially adapted to medium (25 mm) to small size parts.

Table 2.3 Overview of MIM materials, applications, and features

Material family	Applications	Specific alloys	Specific feature
Stainless steel	Medical, electronic, hardware, sporting goods, aerospace, consumer products	17-4PH 316L 420, 440C 310	Strength, heat treatable Corrosion resistance, ductility, non-magnetic Hardness, wear resistance, heat treatable Corrosion and heat resistance
Low-alloy steel	Hardware, bearings, races, consumer goods, machine parts	1000 series 4000 series 52100	Case hardenable General purpose High wear resistance
Tool steel	Wood and metal cutting tools	M2/M4 T15 M42 S7	61–66 HRC 63–68 HRC 65–70 HRC 55–60 HRC
Titanium	Medical, aerospace, consumer products	Ti Ti–6Al–4V	Light weight Light weight, high strength
Copper	Electronic, thermal management	Cu W–Cu, Mo–Cu	High thermal and electrical conductivity High thermal conductivity, low thermal expansion
Magnetic	Electronic, solenoids, armatures, relays	Fe–3%Si Fe–50%Ni Fe–50%Co	Low core losses and high electrical resistivity High permeability and low coercive field Highest magnetic saturation
Tungsten	Military, electronic, sporting goods	W W heavy alloy	Density Density and toughness
Hardmetals	Cutting and wear applications	WC–5Co WC–10Co	Higher hardness Higher toughness
Ceramics	Wear applications, nozzles, ferules	Alumina Zirconia	General purpose High wear resistance

Available materials (PIM)

Unlike die-casting, numerous metals and ceramics can be used with a MIM process. As the processing temperature is low, the metal is molten and do not react with the atmosphere or the mold material itself.

The table above shows typical materials used with MIM processes as well as their domain of applications. As can be seen, the applicability is quite broad and includes a broad set of technological domains.

Part II – Analysis of casting

In this second part, we discuss some generic aspects of casting.

Physics of casting...

- **Fluid mechanics** (Mold filling)
- **Heat transfer** (solidification)
- **Thermodynamics** (material phase, grain nucleation, growth)
- **Material behavior** (structural properties)

Casting is a multidisciplinary field that includes results from thermodynamics, fluidics and mechanics.

Key physics parameters in a casting process

- Mold temperature
- Hot metal temperature
- Flow rate
- Mold volume distribution

Affects →

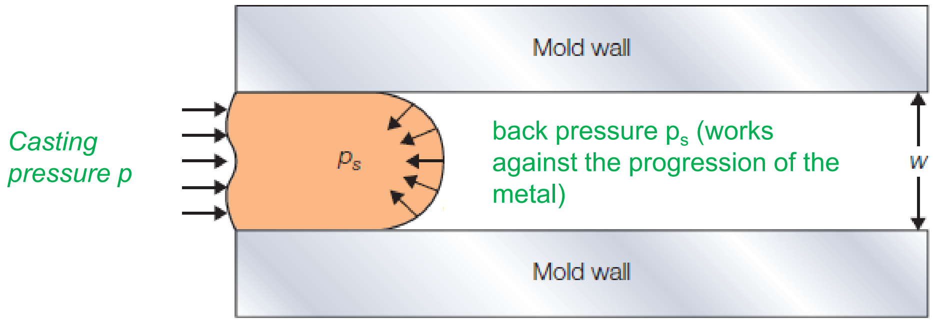
- *Metal solidification rates*
- *Mold filling*
- *Materials microstructures*

As can be devised intuitively, there are four main parameters that come into play. The mold temperature, the filling metal, the flow rate and the mold volume distribution (e.g., how mass and volume are distributed).

All these parameters will define the metal solidification rate, the mold filling homogeneity as well as the fine microstructures of the material.

Limit of casting

- Dependence on **flow pressure** of metal through the channels



$$p_s \propto \frac{\gamma}{r}$$

Surface tension of the hot metal (N/m)

Radius of the meniscus (= w/2)

Infiltration if:

$$p > p_s$$

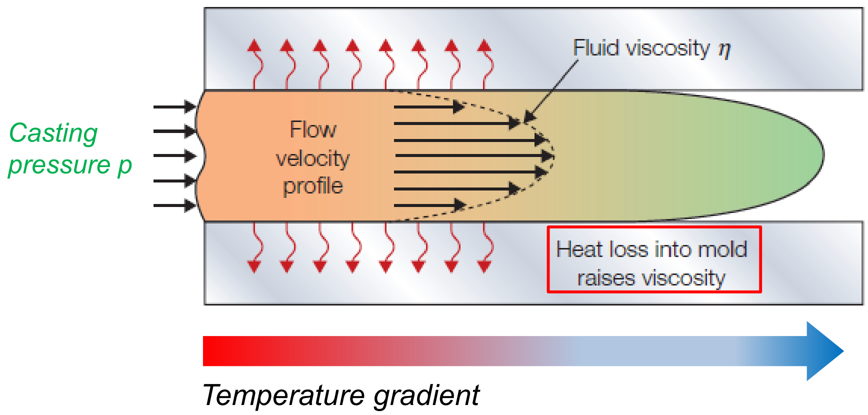
Let us consider a thin cylindrical channel in which a hot fluid is pushed through. In such case, the casting pressure – the pressure requires to push the metal in will have to overcome the back pressure (p_s).

This back pressure essentially originates from the surface tension of the liquid metal with the mold wall and the radius of the meniscus formed.

Hence, for a given hot metal and a given channel size, one can estimate the required pressured to achieve infiltration.

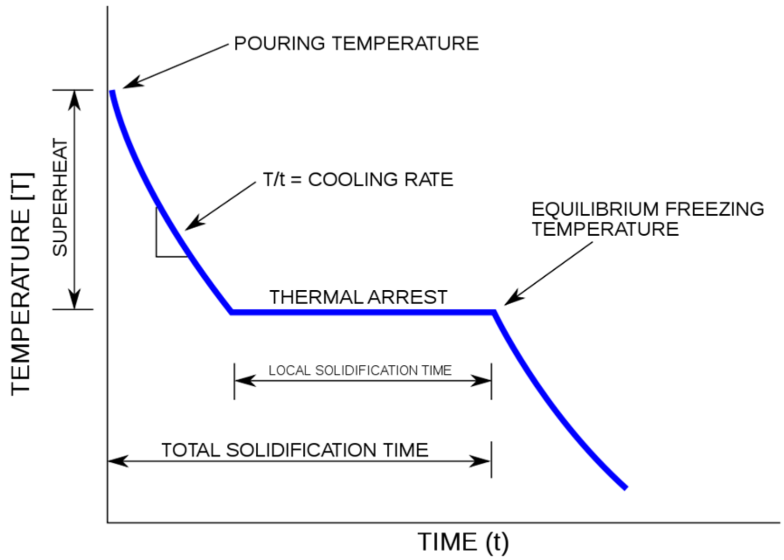
Limit of casting

- Dependence of the **solidification rate**



However, the previous description assumes that the temperature is constant. While this can be true in a first approximation and for a high-speed infiltration, in reality the heat loss into the mold will raise the viscosity of the metal and consequently the force required to push the metal in, up to the point, where it is no longer possible because the metal has solidified.

Solidification of a pure metal



Adapted from Degarmo, E. Paul; Black, J T.; Kohser, Ronald A. (2003), Materials and Processes in Manufacturing (9th ed.), Wiley, ISBN 0-471-65653-4.

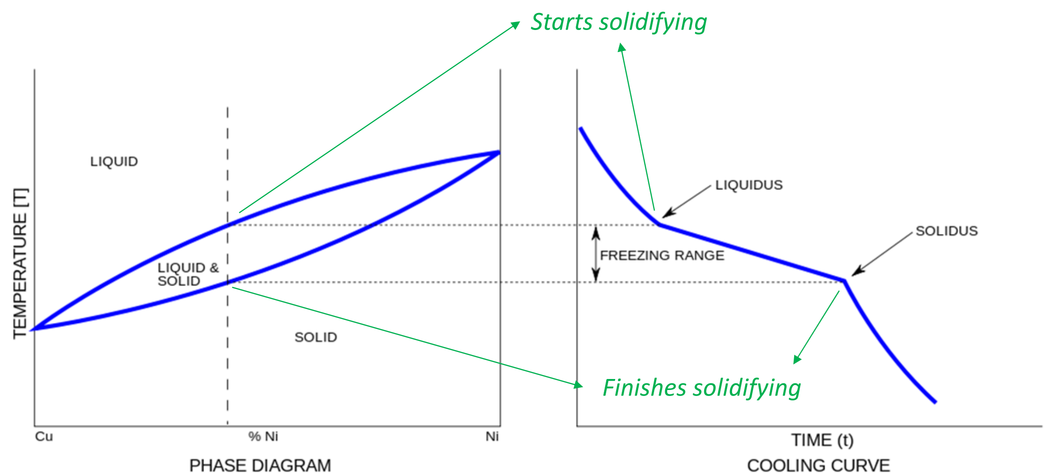
The solidification process will be different whether one consider a pure metal or an alloy. The curve above shows the solidification curve of a pure metal as it solidifies. Let us consider that a pure metal (i.e., one constituent only – like for instance pure silver or gold) is poured at a time t = 0. The curve above shows how the temperature evolves as the liquid metal solidifies.

The solidification will start once a critical temperature is reached ('the equilibrium freezing temperature'. Interestingly, at this point the temperature will remain constant while the metal solidifies. Once the liquid has completely turned into a solid, the metal temperature continues to decay until it reaches room temperature.

The total solidification time will then include the time for the liquid to reach the freezing temperature *plus* the so-called 'thermal-arrest'. Hence, solidification does not 'instantaneously' occur at the freezing temperature, but takes a certain time.

This discontinuity in the cooling process is typical of a first-order transformation in physics.

Solidification of an alloy (ex. Cu/Ni)



Adapted from a diagram from Degarmo, E. Paul; Black, J T.; Kohser, Ronald A. (2003), Materials and Processes in Manufacturing (9th ed.), Wiley, ISBN 0-471-65653-4.

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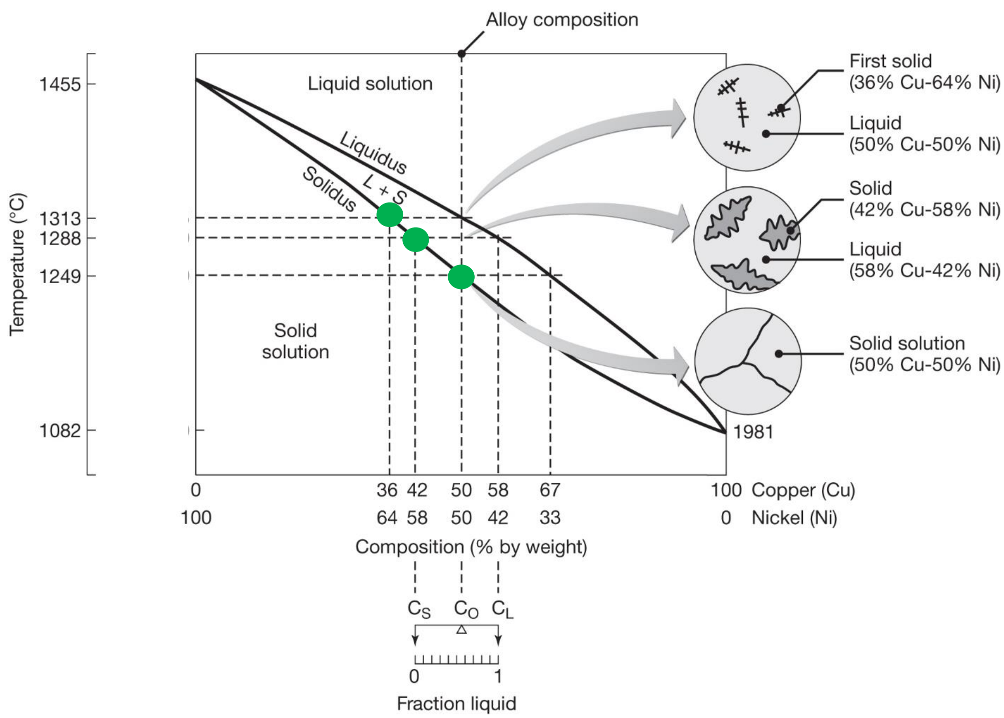
In most metal molding process, the metal is not pure but rather is made of multiple atomic constituents. In such case, one talks about an alloy.

In such cases, the solidification curve is different and no longer has this characteristic discontinuity.

An illustration is shown above for a binary alloy of Cu/Ni. The solidification dynamics will depend on the phase diagram that represents the characteristics temperature of solid/liquid transition as a function of the percentage of the constituents.

In the example above, solidification starts when the temperature crosses the 'liquidus' curve and continues until it reaches the characteristic 'solidus' curve.



(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

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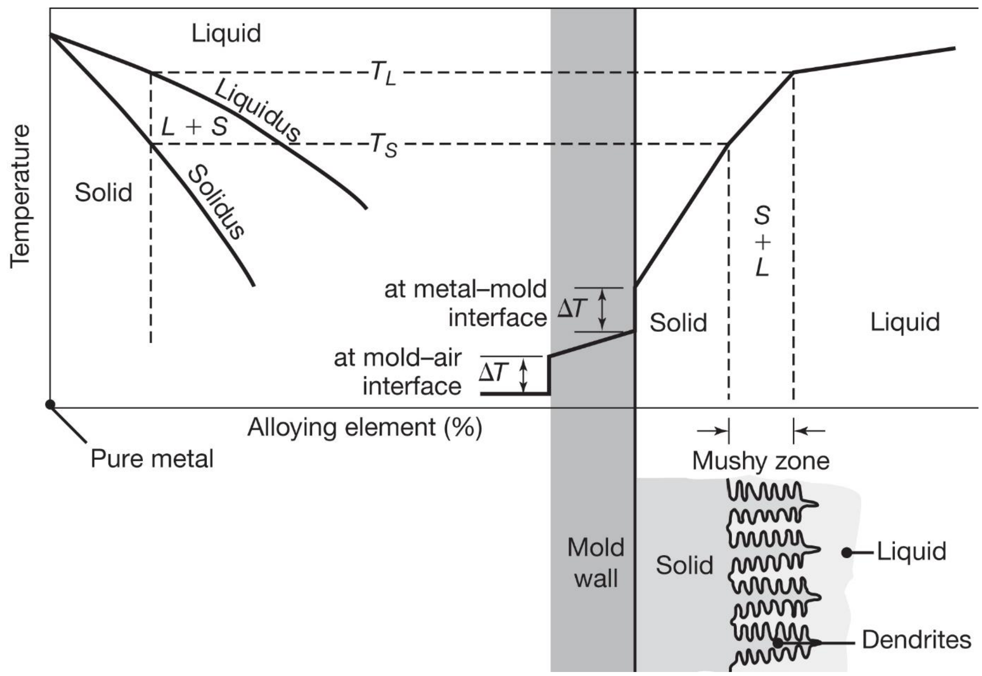
In the zone found in between the liquidus and solidus curves, the material has a two-phase structure, where metal particles in formation are in solution with the liquid. In this zone, the composition of the metallic phase can be found using the lever methods, schematically described above. This metal phase will grow and eventually form grains in the solidified structure.



(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

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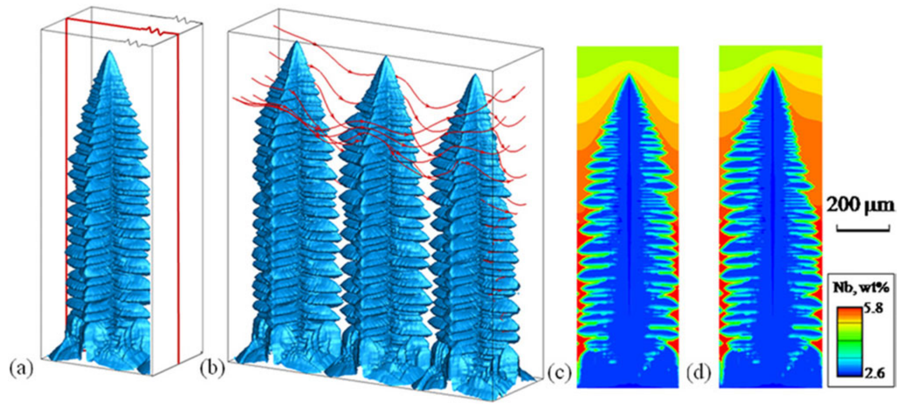
Keeping in mind this solidification curve, let us examine how the solidification process can proceed in a mold.

Solidification will start at the lowest temperature point, and hence on the mold wall and then progresses inward following the temperature gradient.

Specific microstructures may form, like for instance dendrites that are a subtle interplay between nucleation, phase growth and concentration/temperature gradients.

Solidification (Alloys): Dendrites

Snowflake

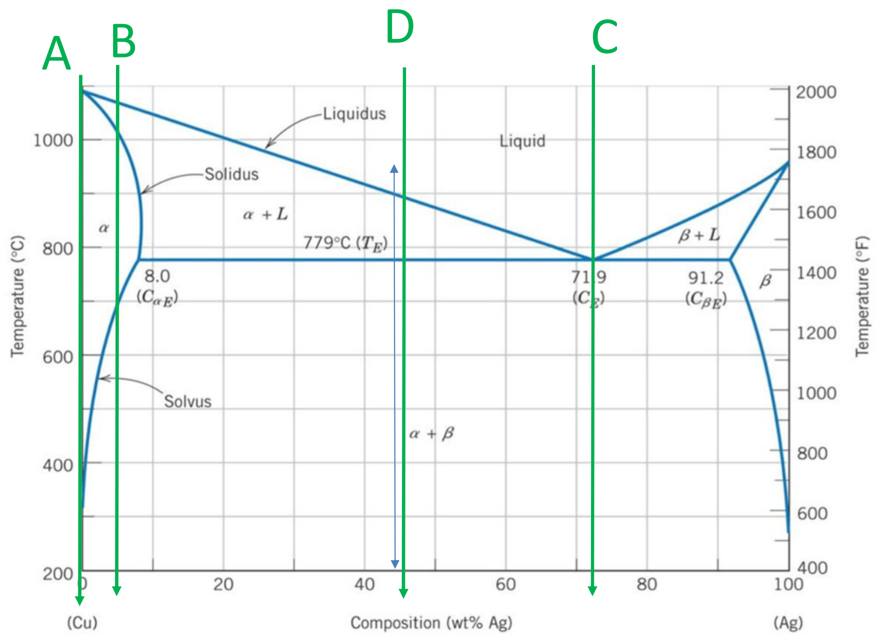


Lang Yuan and Peter D Lee, Dendritic solidification under natural and forced convection in binary alloys: 2D versus 3D simulation, Modelling Simul. Mater. Sci. Eng. ***18*** *(2010) 055008 (13pp)*

If you are curious about dendrites: (Seminar from P. Voorhees, Northwestern Univ.) https://youtu.be/W-yHaZqRrBU

Dendrites are remarkable examples of self-organized structures forming during solidification. Studying them goes beyond the scope of this class, but if you are interested in exploring the topic further, we recommend the link above to a seminar given by P. Voorhees at Northwestern University.

Exercise (homework): describe the material structure evolution for A, B, C, D (Cooling from the liquid phase to the solid ones)



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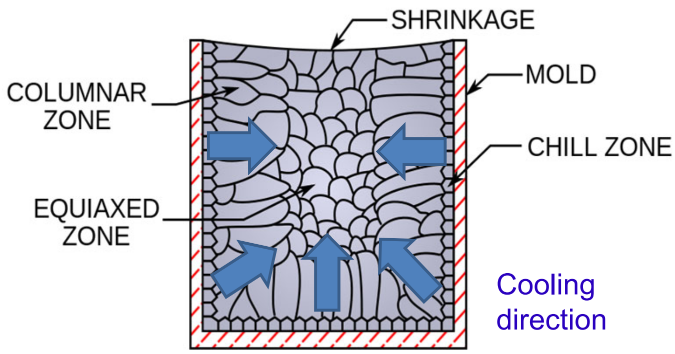
Phase diagram can be significantly more complex than in the previous example. Depending on the possible crystallographic phase that can be formed, multiple zones can be defined.

As an exercise (based on your previous materials science studies), try to describe the material structure following the solidification path A, B, C and D.

Typical microstructure of a cast ingot



[Adapted from: C. Dang Ngoc Chan (Wiki)]

Image: H. K. D. H. Bhadeshia, Cambridge Univ.

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How solidification progresses will have a direct impact on the material microstructure. It will depend on various aspects, such as the cooling front, the metal and the geometry of the mold.

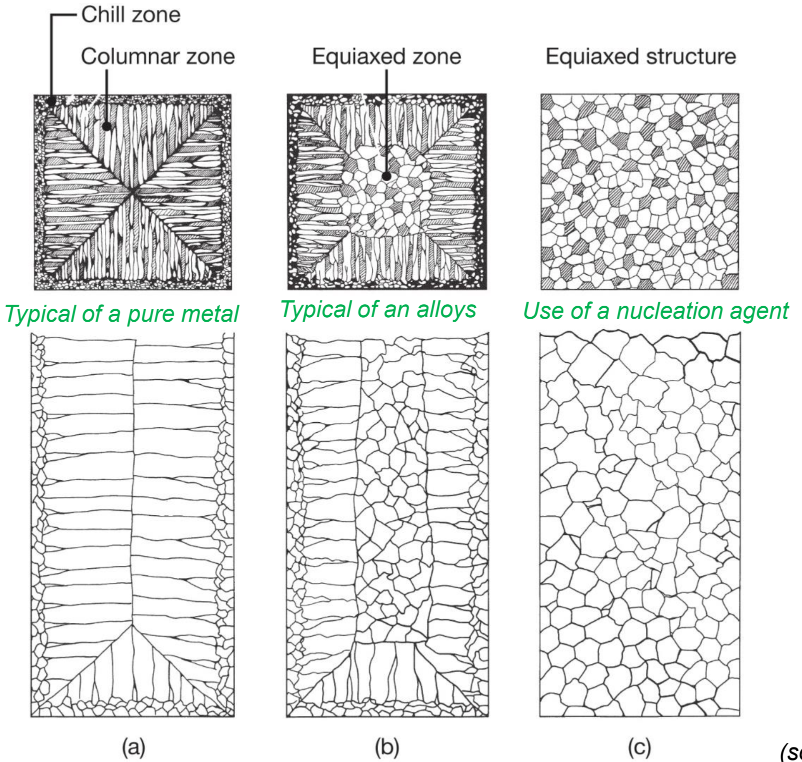
The image on the right shows a beautiful example of a solidified ingot and its microstructure. Notice the differences between the grain orientations and sizes from the edges and the one in the middle of the cast.

Notice also the shrinkage occurring at the top part of the cylinder, where the metal surface was free.

Indeed, one should not forget that metal solidifying will shrink of volume, while being transformed from a liquid phase. The amount of shrinkage will depend on the metal but is not negligible in most cases.

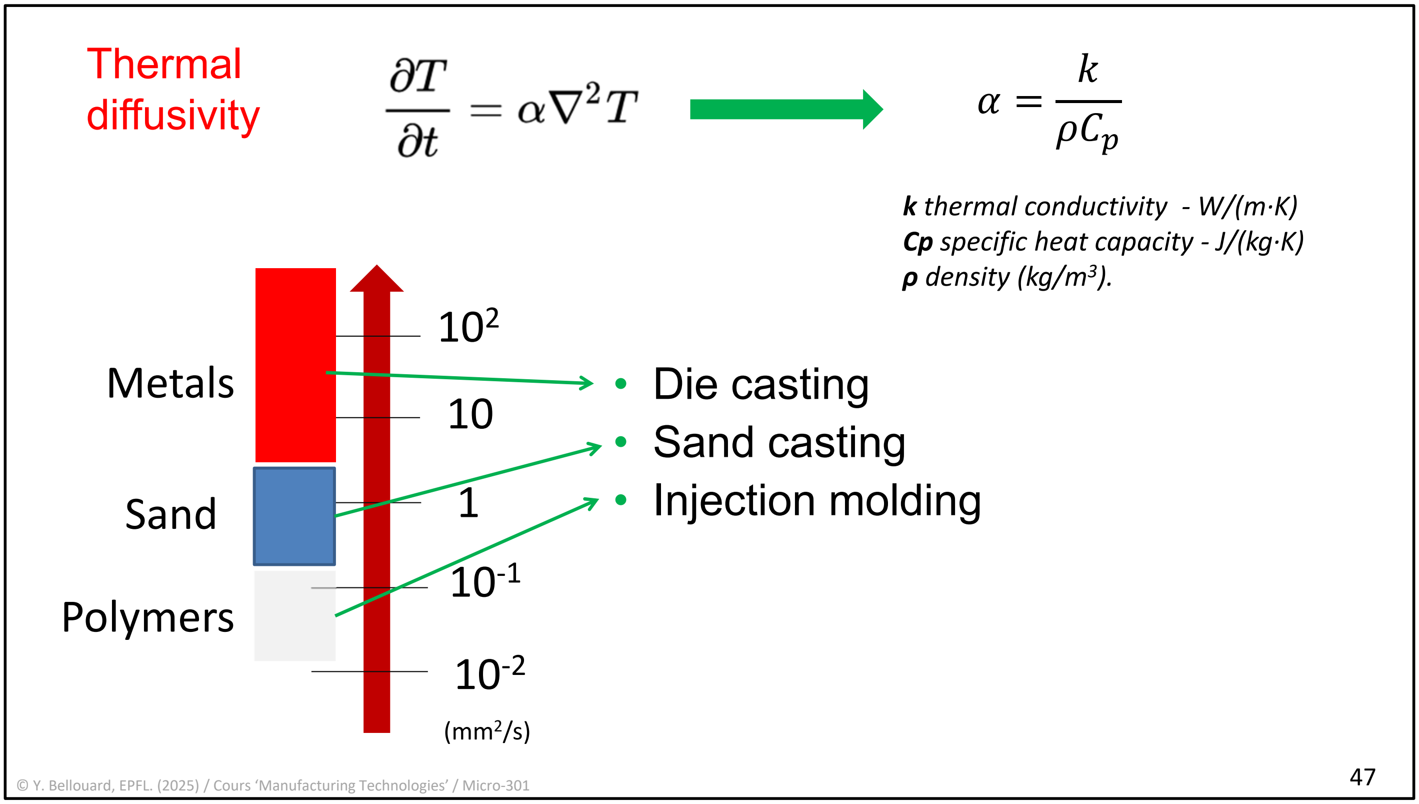
All these aspects will be to be taken into account, while designing a molding process, to ensure that the mold is uniformly filled at the end and that the microstructure is controlled.

Example of solidified microstructures



(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

In addition to the parameters discussed before, the final microstructure of the metal will also depend on the composition of the metal, whether it is a metal or an alloys, and for instance if additional element are used to facilitate the nucleation of a solid phase in the liquid one during solidification.



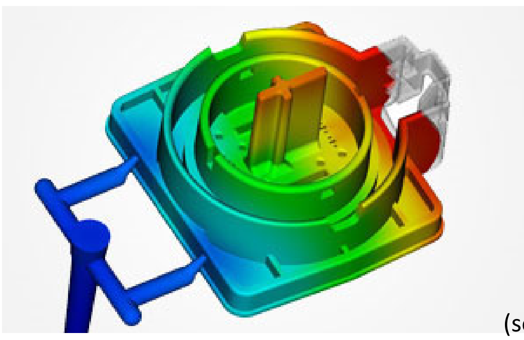
An important parameter ruling the dynamics of cooling processes is the diffusivity that describes how fast can heat spread in a given material.

For instance, there are order of magnitude of differences whether one consider a metal, sand or a polymer.

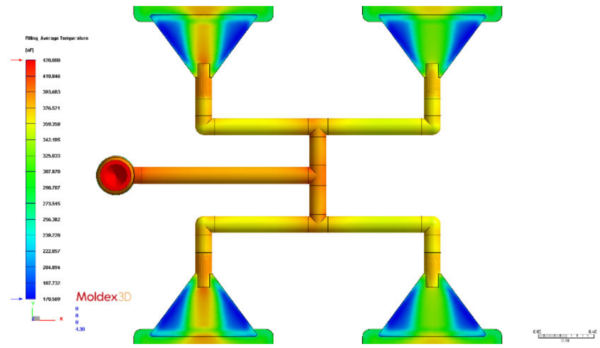
This observation has an impact on how molding processes can be designed and implemented in practice.

Thermal analysis

- Chvorinov's model assumptions
  - One d model
  - Mold and metal have constant density, heat capacity, heat conductivity.
  - Metal has similar thermal properties in liquid and solid phase.
- Note that molding flow and temperature are nowadays simulated with CAD software.



(source: Moldex)



Considering the importance of controlling the temperature in designing a molding process, it is important to define some methods to predict where solidification will occur and in what order.

For a generic understanding, we will discuss a one-dimensional model, the so-called 'Chvorinov's rule'. This model gives an intuitive understanding on the process.

Nowadays, thanks to the availability of powerful computing means, for predicting the thermal behavior of complex parts, it is common to make use of simulation software (such SolidWorks Plastics, AutoDesk Moldflow, etc. among many) to accurately predict a molding process.

But just like for mechanical design, it is useful to have a high-level intuition on how to avoid solidification issues through smart mold design. This understanding greatly facilitates the final design of the mold that can be further optimized using a FEM software.

Cooling time (Chvorinov's rule)

Use to estimate solidification time

$$t = B\left(\frac{V}{A}\right)^n$$

Constant / usually 2...

Volume solidifying

Surface solidifying

$$B = \left[\frac{\rho_m L}{(T_m - T_o)}\right]^2 \left[\frac{\pi}{4k\rho c}\right] \left[1 + \left(\frac{c_m \Delta T_s}{L}\right)^2\right]$$

T_m = melting or freezing temperature of the liquid (in Kelvin)
T_o = initial temperature of the mold (in Kelvin)
$\Delta T_s = T_{pour} - T_m$ = superheat (in Kelvin)
L = latent heat of fusion (in $[J \cdot kg^{-1}]$)
k = thermal conductivity of the mold (in $[W \cdot m^{-1} \cdot K^{-1}]$)
ρ = density of the mold (in $[kg \cdot m^{-3}]$)
c = specific heat of the mold (in $[J \cdot kg^{-1} \cdot K^{-1}]$)
ρ_m = density of the metal (in $[kg \cdot m^{-3}]$)
c_m = specific heat of the metal (in $[J \cdot kg^{-1} \cdot K^{-1}]$)

The Chvorinov's rule predicts the cooling time based on the volume to surface ratio as well as various material parameters.

Logically, the bigger the volume to surface ratio, the longer it takes to solidifies. For instance, a sphere would take much longer to solidify than a rectangular plate.

Application of Chvorinov's rules

- Typical use is to ensure that **the riser** cools **after** the **casting**
- Typical rule of thumbs:

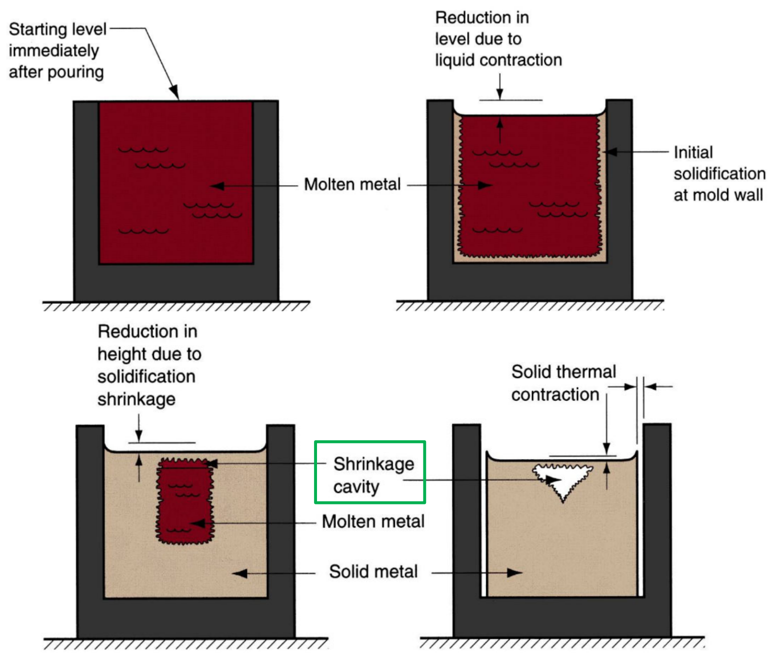
$$\left(\frac{V_{riser}}{A_{riser}}\right)^n \approx 1.25\left(\frac{V_{casting}}{A_{casting}}\right)^n$$

An illustration of the use of the Chvorinov's rule is for risers.
Risers are used to maintain a feed of liquid metal during shrinkage hence it is important they cool *after* the volume being cast.

Solidification shrinkage

- For most materials, when solidification occurs, their volume shrinks
- Solidification process is a dynamic effect that can lead to undesired effect if not controlled

Concept of directional solidification



(Note that dimensions are exaggerated for the sake of understanding)

Illustrations adapted from Seok-min Kim (Cung-An Univ.), lecture notes

Controlling shrinkage is indeed one of the challenges in molding. To illustrate this point, let us consider the simple example depicted above.

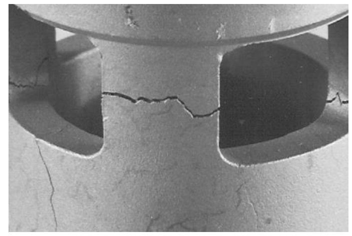
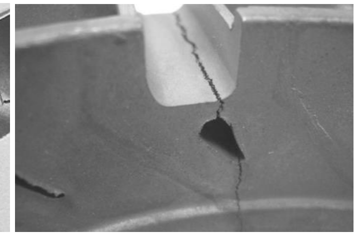
A simple volume is fed with a metal in its liquid state. Solidification will first start from the edges. As solidification progresses, a volume shrinkage will occur. Let us assume now that the upper part starts solidifying, what may happen is that, during shrinkage and because of the solidification dynamics, a cavity forms in the volume.

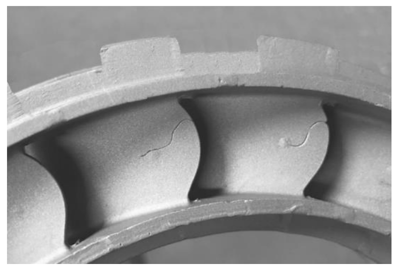
Hence, if not controlled, solidification can lead to undesired effects among the formation of cavities, cracks, etc. (see next slide)

It is therefore important to control it, which brings us to the important concept of *directional solidification*.

Typical casting defects

- Shrinkage, fractures
- Impurities
- Pouring defects
  - *Misruns:* metal does not completely fill the cavity
  - *Cold-shuts:* 'cold welding'
- Gas bubbles
  - Gas trapped in the liquid form cannot escape during solidification (typ. H_2, O_2, N_2)



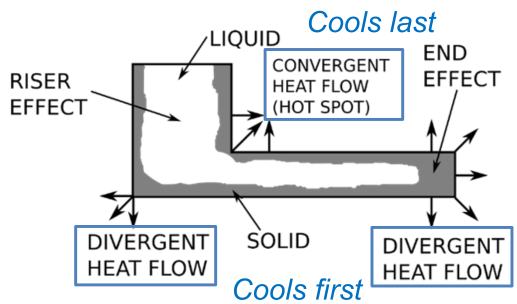

'Atlas of possible defects'
https://61746c6173.investmentcasting.org/casting/defects/index.html

(Illustrations / Investment Casting Institute)

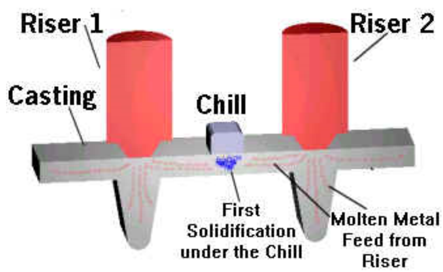
The pictures above, taken from real examples, illustrate various examples of casting defects occurring during solidification. From cavities, to cracks or impurities, defects resulting from an improper mold-design or uncontrolled solidification.

Directional solidification

- Geometries introduce **anisotropic temperature distributions**
- **Solidification** does not start at the same time everywhere



(source adapted from Wiki)



- Goal is to control a **temperature gradient to force directional solidification**
- This can be done by disposing **chillers** ('Voleur de chaleur') at certain locations to force the solidification to start at a specific point

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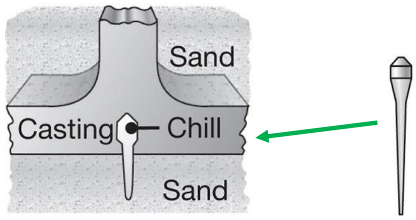
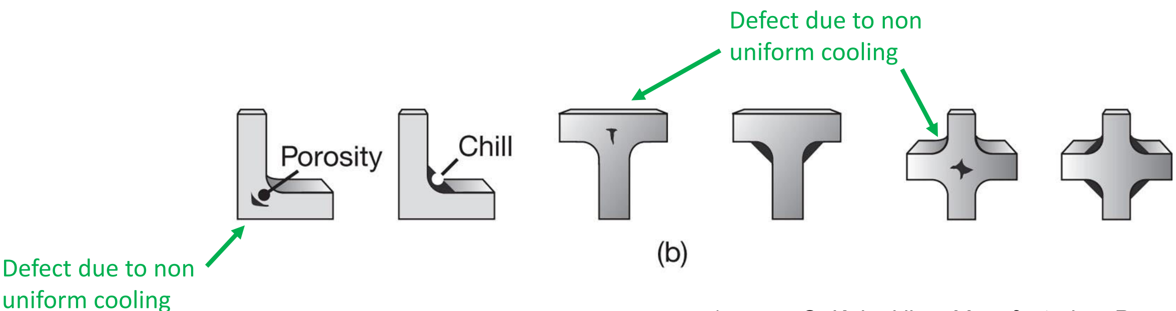
As illustrated above, directional solidification depends on the geometry of the mold and does not start homogeneously everywhere in the mold.

To homogenize the process and/or to define where solidification should start first, additional elements such as risers and chillers ('voleurs de chaleur') can be added in defined places on the mold geometry.

Example of technical solution for controlling solidification ('chills') / Directional solidification



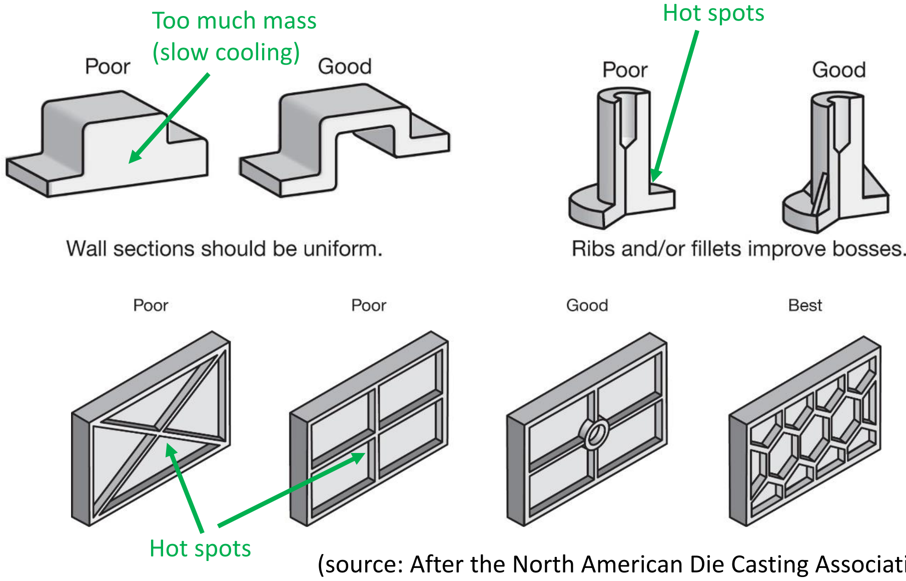
Chillers are pieces with various geometries made of material with good calorific properties as 'heat absorbers'



(source: S. Kalpakjian, Manufacturing, Pearson Ed.)

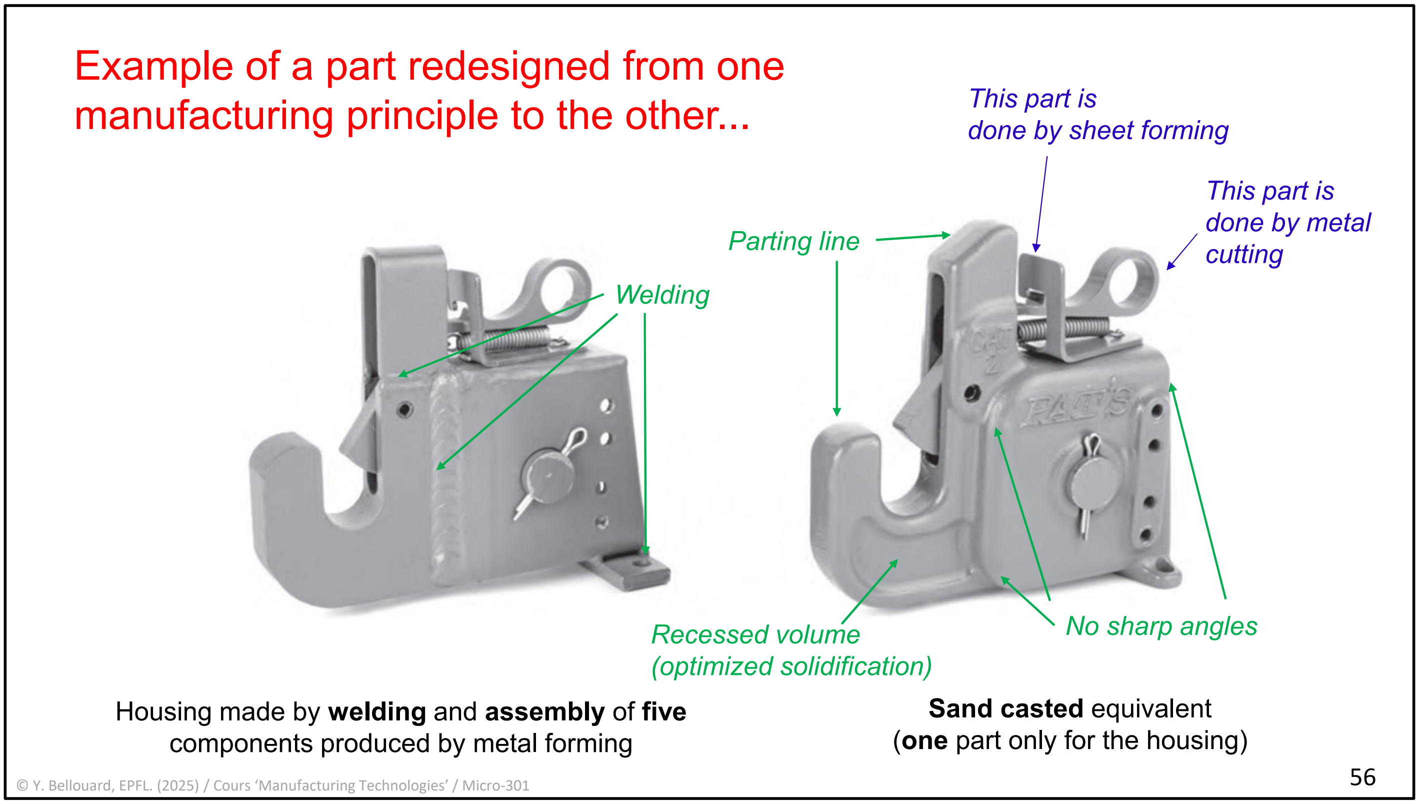
Here are a few examples where the use of additional elements can be used to prevent non-uniform cooling eventually leading to defects.

Example of corrective actions through mold design (empiric) principles



(source: After the North American Die Casting Association
S. Kalpakjian, Manufacturing, Pearson Ed.)

Likewise, a part design will be specifically adapted for molding to anticipate the solidification process. A few examples of design rules are shown above.



This illustration shows the same part made using two different process flows.

The left one was made using parts made by metal forming welded together. The right part was done using sand casting for the main body.

Although the two parts have exactly the same function, one can note the differences between them. In both cases, this is to adapt the part design for optimal use of the selected manufacturing process.

This is an important point in manufacturing. As seen in the first lecture, there is an intimate link between a design and a manufacturing process. A part is not only design to fulfil a design requirements, but also to be optimally produced according a selected manufacturing process.

Part III / Illustrative example of ongoing research at EPFL

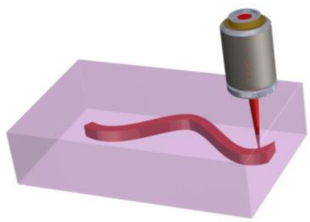
(Galatea Lab / Laboratory of Mechanical Metallurgy)

In this final part, we show an example of ongoing research to extend casting processes to the micro-scale.

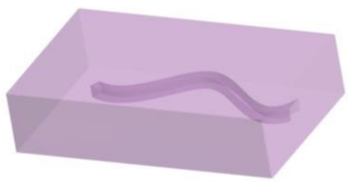
This is process was developed at EPFL, jointly by the Galatea Laboratory of Prof. Yves Bellouard and the Laboratory of Mechanical Metallurgy of Prof. Andreas Mortensen.

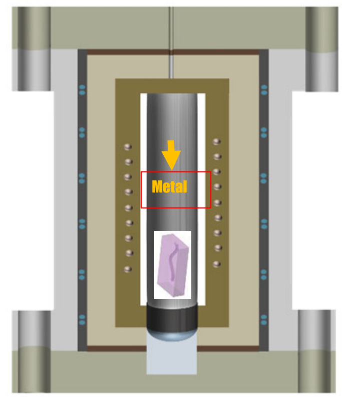
Basic idea

Step 1 / Femtosecond laser exposure



Step 2 / Etching step



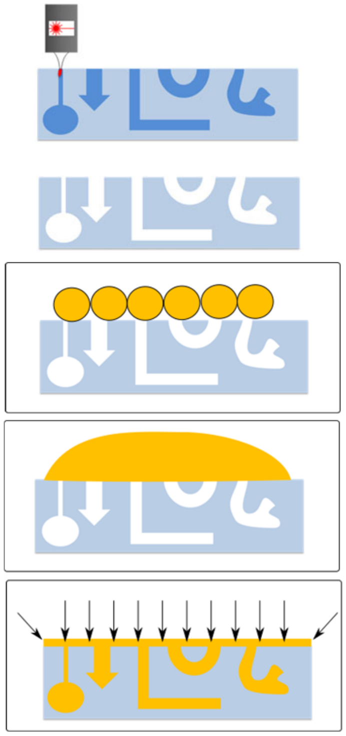


Step 3 / Pressurized metal infiltration under vaccuum

The basic idea is to combine a process based on femtosecond laser exposure and a process based on micro-scale infiltration of metals.

The mold here is a glass piece made of fused silica. The material has similar thermal properties than sand, hence a low diffusivity.

3D-micro-casting: process



Step 1 – '3D pattern definition' / Femtosecond laser exposure

Step 2 – '3D Cavities' / Etching step (HF or KOH)

Step 3 – Feed material / Specimen is placed in a high-temperature pressure/vacuum chamber (1 mBar)

Step 4 – Metal is molten forming a liquid interface / T reaches > 1000 C

Step 5 – Gas (Ar) is fed into the chamber / pressure reaches 100 bar (10 MPa)

L. Borasi, E. Casamenti, R. Charvet, C. Dénéréaz, S. Pollonghini, L. Deillon, T. Yang, F. Ebrahim, A. Mortensen, and Y. Bellouard, "3D metal freeform micromanufacturing," Journal of Manufacturing Processes ***68****, 867–876 (2021).*

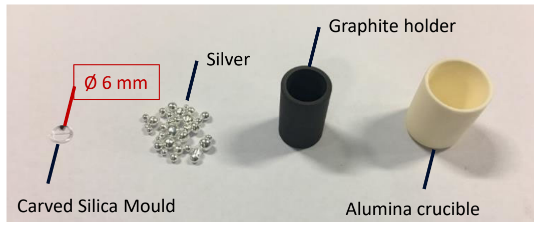
The process steps are described above.

The **first step** (3D Laser-lithography) is to expose the glass to femtosecond laser to form three-dimensional patterns. The **second step** is a chemical etching, during which exposed volumes are etched away. In the **third step**, the material is put in vacuum and a feedstock of metal is placed above. The feedstock consists of pellets of metal.

The part is then heated to the melting point of the metal, which melts and wet the glass mold (**step four**) sealing the cavities formed by microfabrication. In the last step, gas is fed into the chamber at a pressure of 100 bars (i.e., 10 MPa). The pressure difference between the sealed vacuum cavities and the gas pressure pushed the metal to infiltrate the cavities.

3D-micro-casting: Process

Enables the freeform fabrication of **3D** complex metal micro-parts with the potential for **sub-micron** resolution

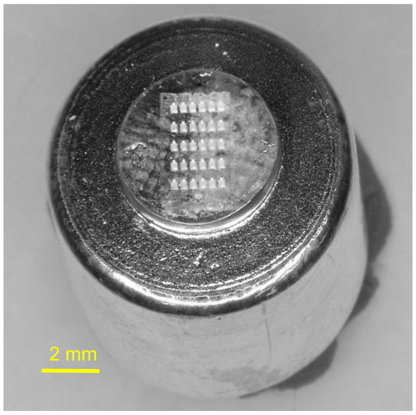


L. Borasi, E. Casamenti, R. Charvet, C. Dénéréaz, S. Pollonghini, L. Deillon, T. Yang, F. Ebrahim, A. Mortensen, and Y. Bellouard, "3D metal freeform micromanufacturing," Journal of Manufacturing Processes ***68****, 867–876 (2021).*

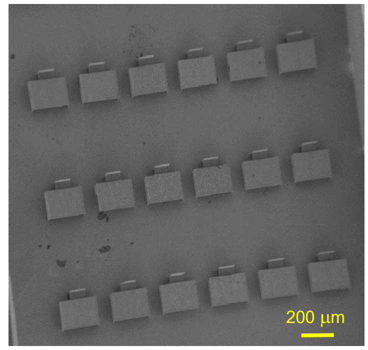
The picture above shows the various elements of the process: the carved silica mold (6 mm in diameter), metal feeds, and the various crucible and holders.

The version above is for a research phase, not a production.

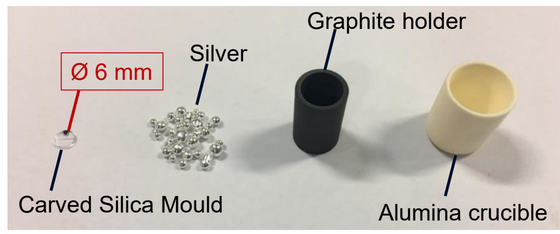
Combine metal infiltration and femtosecond laser glass 3D machining



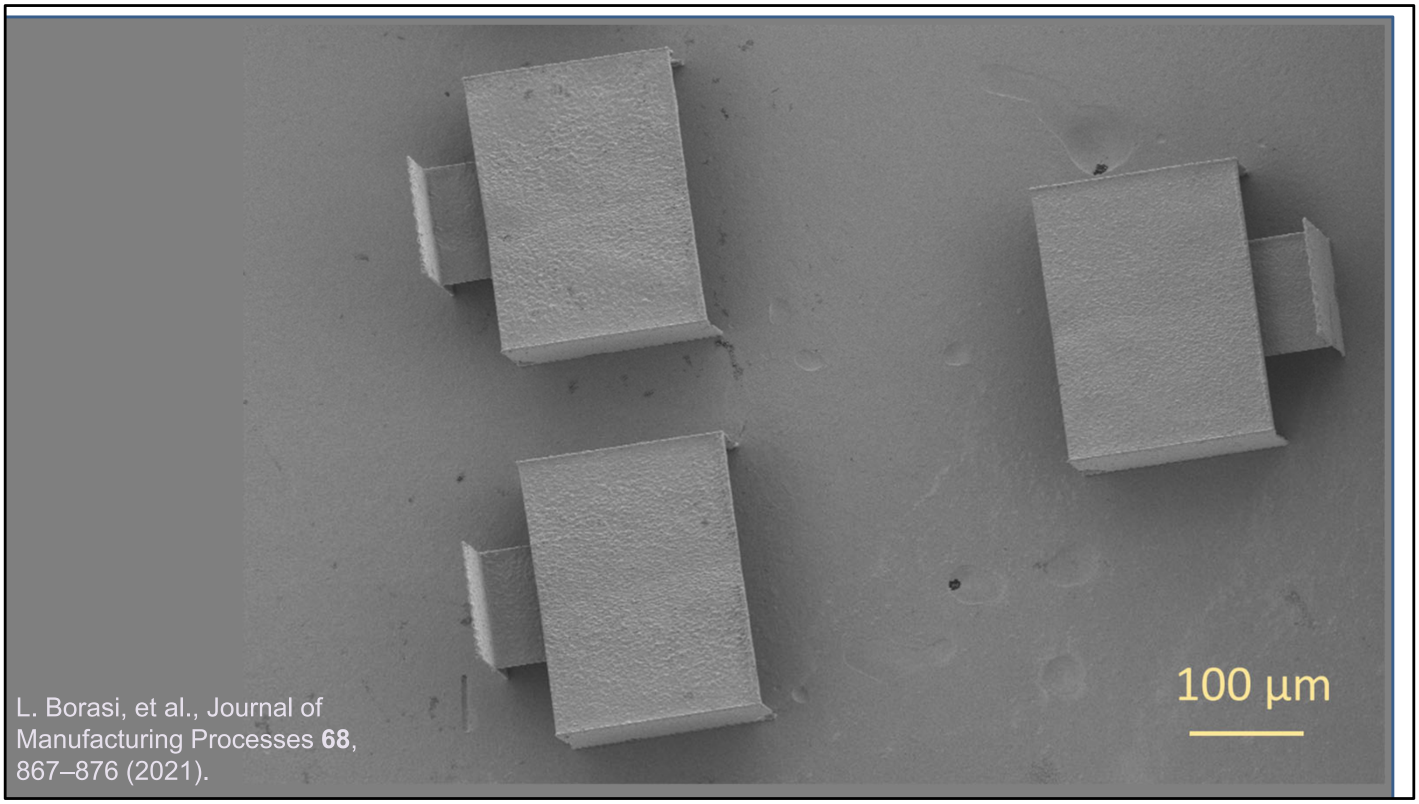
SEM view (substrate removed)



Substrate infiltration

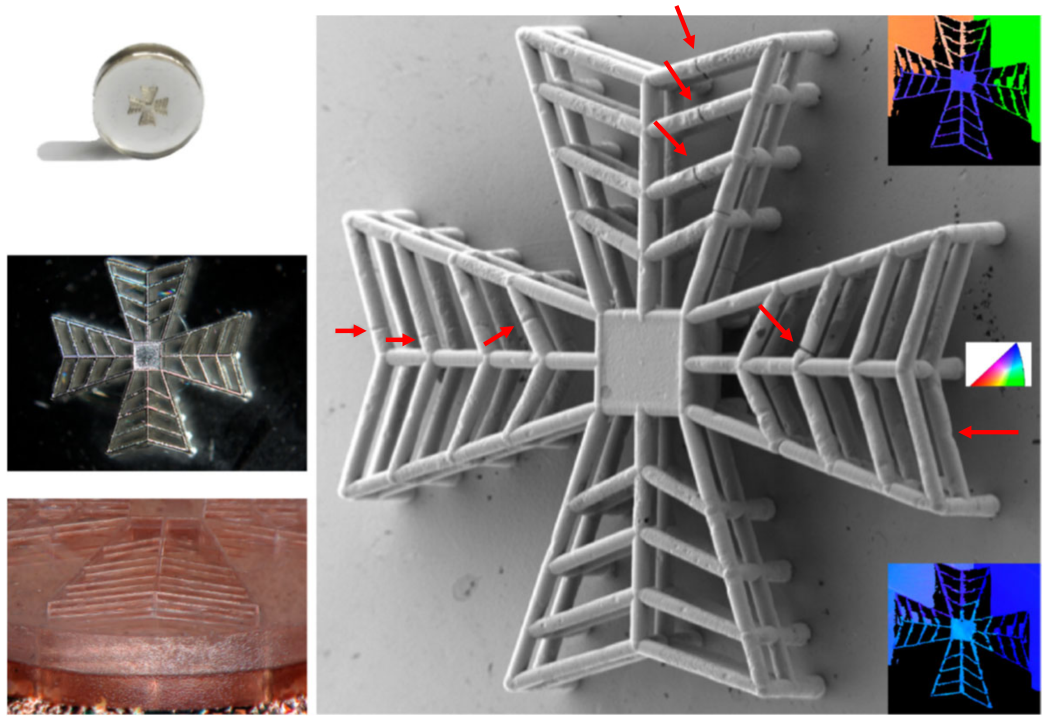


An example of part produced according this process: a 'micro-scale' class room.



A close-up view of the micro-scale class room seen in an scanning electron microscope. The structure are three-dimensional and made of pure silver.

Illustration

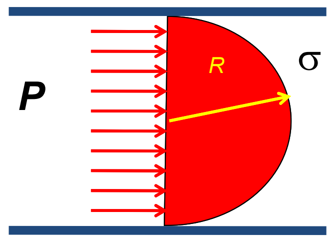


Another example of part, this time made out of copper. The Malta cross is made of three crystal grain. The boundary of the grain are highlighted with red arrows.

Scaling effect in casting

- **High aspect ratio** (>1:100), **3D** cavities with **sub-micron** resolution in **a high melting point** (>1200 deg. C) substrate
- Surface tension ($\sigma \approx 1$ J . m^{-2}) of **metals** requires **10 MPa** to infiltrate features down to **100 nm** ($P \approx \sigma/R$)

$P \approx R^{-1}$ MPa
if R is in µm



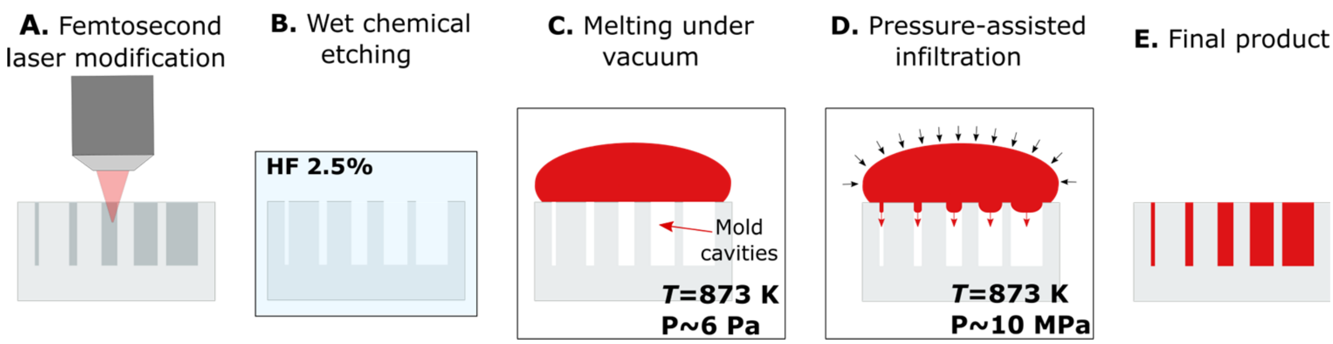
Combining femtosecond laser machining with pressure infiltration has the potential to produce ***3D metal parts*** *with* ***0.1 µm*** *feature resolution*

One can estimate what is the minimum channels that can be infiltrated, considering the pressure applied.

The surface tension of metal is typically 1 J m^{-2}. With 10 MPa, the minimum channel size would be 100 nm.

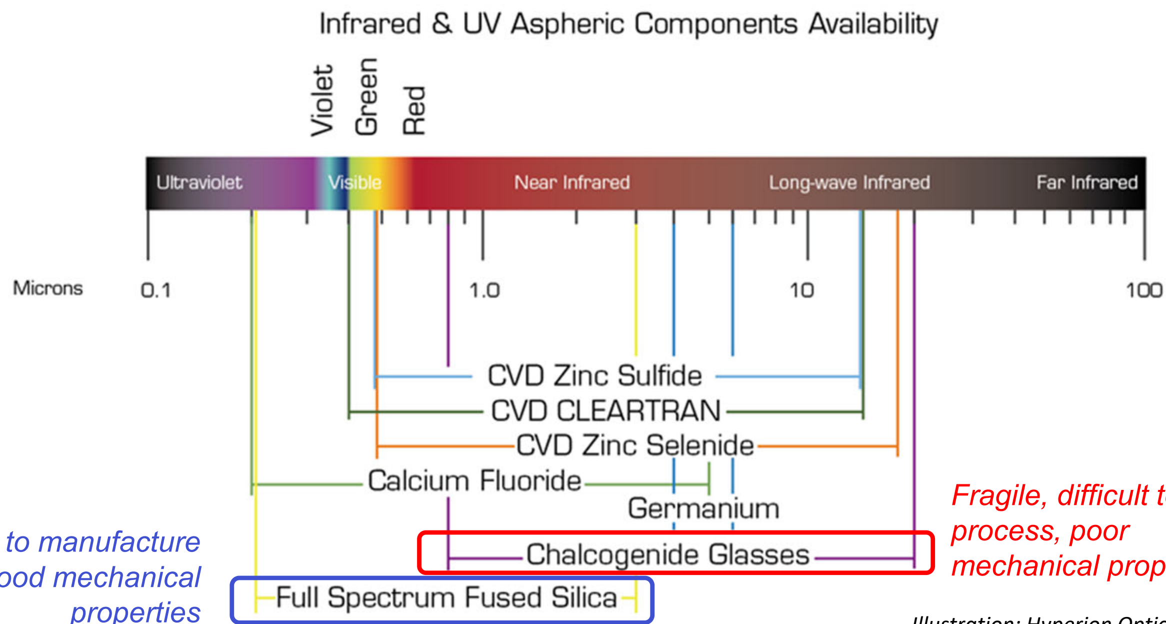
‘Glass-in-glass’: Process workflow

- Some glass have good optical properties, but poor mechanical properties / manufacturability, and vice-versa.
- *Rationale: Mix the best of both world!*



The process has later been extended to glass infiltration. There the same is used to infiltrate a fragile infrared glass with low melting point in a more robust glass, fused silica.

IR glass into silica: the best of both world...



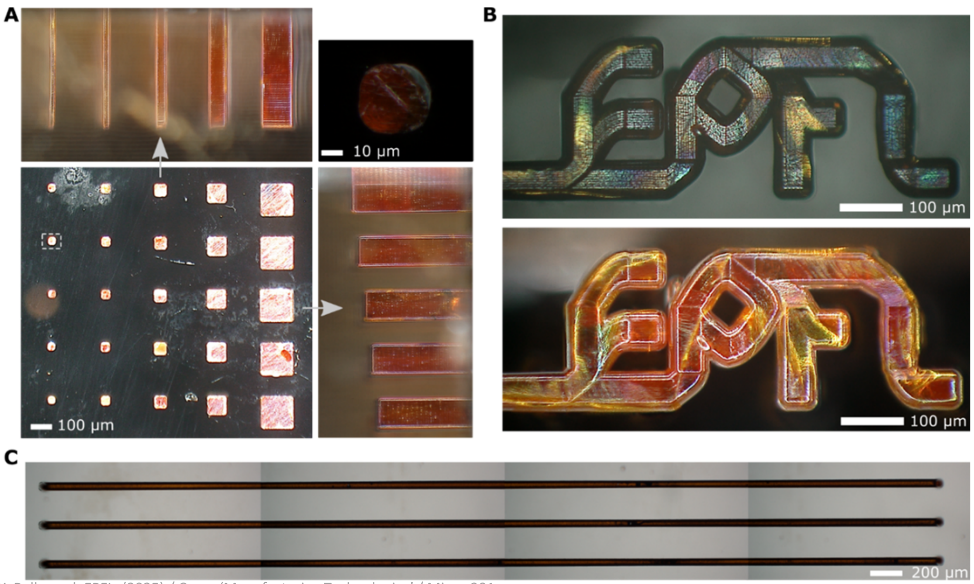
Easy to manufacture
Good mechanical properties

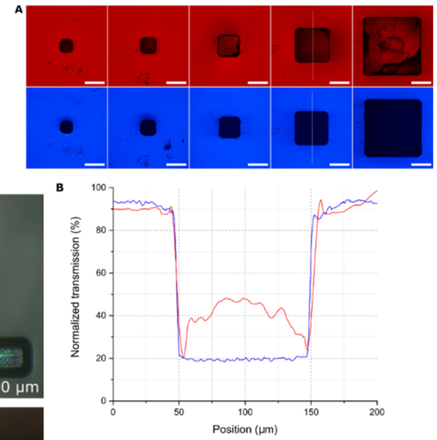
Fragile, difficult to process, poor mechanical properties...

Illustration: Hyperion Optics

The interest here is to produce parts with arbitrary shapes, made of IR glass.

Illustration:
Chalcogenide glass into silica





E. Casamenti, G. Torun, L. Borasi, M. Lautenbacher, M. Bertrand, J. Faist, A. Mortensen, and Y. Bellouard, "Glass-in-glass infiltration for 3D micro-optical composite components," Opt. Express **30**, 13603 (2022).

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Illustrations of IR glass (appearing in orange on the image) infiltrate in a glass host.

Wrap-up / Things to remember

- The three main types of casting methods:
  - Sand casting
  - Lost-wax
  - Dye casting
  - Metal injection molding (MIM) process
- Solidification process
  - Solidification front
  - Solidification shrinkage
  - Chvorinov's rule
- An illustration of the link between design and manufacturing

'Lexique manufacturing'

English (UK) > French

- Casting of metals: *Coulage des métaux*
- Gating systems: *système de remplissage*
- Sand casting: *Moulage au sable*
- Lost-wax casting: *Moulage à la cire perdue*
- Dye casting: *Injection des métaux*
- Chill: *Voleur de chaleur*
- Dendrite: *Dendrite*
- Riser: *Masselotte*
- Metal Injection Molding: *Moulage par injection des métaux*
- Sprue: Carotte de coulée, carotte d'injection
- Runner: Canal chaud