ME 4563

Introduction to Manufacturing Processes

College of Engineering
Arkansas State University

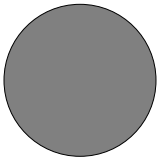
Casting Processes for Liquid Metals

- There are two classes of casting processes:
  - Ingot casting - simple shapes for subsequent processing
  - Net shape casting
- Ferrous-alloy Ingots: depending upon the amount of gas evolved during solidification of the ingot, three types of steel ingots can be produced – killed steel, semi-killed steel and rimmed steel

Ingots

Rolling Ingot

Extrusion Ingot



- Disadvantages of ingots
  - Often need scalping to provide good surface finish
  - Require energy to homogenize/reheat
  - Handling 20-40 ton slabs is difficult
  - It is an extra step which adds costs

Continuous Casting

- Continuous Casting is the process whereby molten steel is solidified into a "semi-finished" billet, bloom, or slab for subsequent rolling in the finishing mills

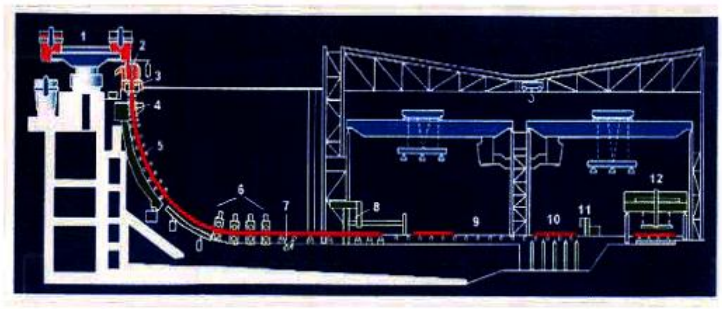
- Prior to the introduction of Continuous Casting in the 1950s, steel was poured into stationary molds to form "ingots"

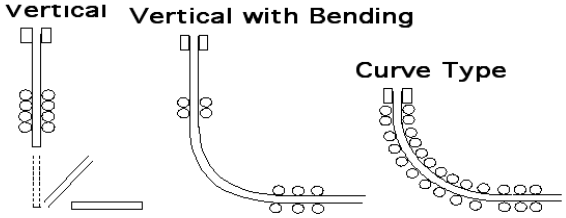
- Since then, "continuous casting" has evolved to achieve improved yield, quality, productivity and cost efficiency

Continuous Casting

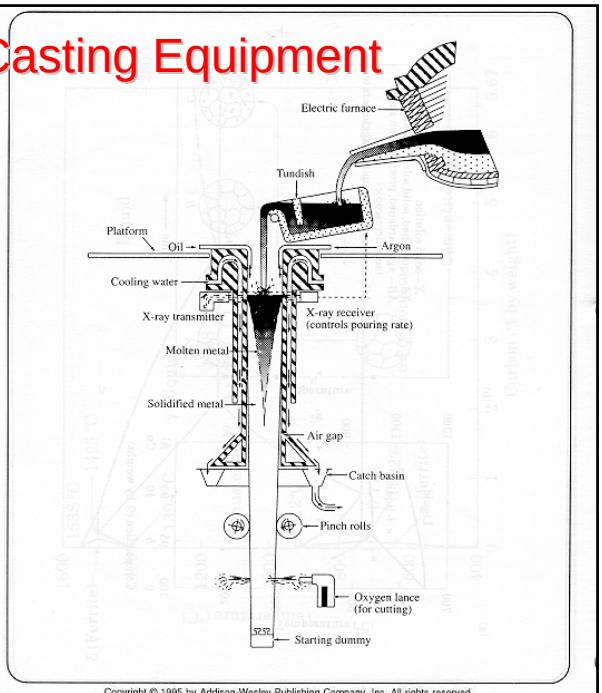
- Remove bottom of mold and continually pull slab out of mold - a continuous billet
- Advantages
  - Lowers cost
  - Continuous production
- Disadvantage
  - Difficult to control
  - Grain structure of cast material not entirely eliminated because the hot deformation is less
  - Difficult to change material
  - Difficult to start and stop

Continuous Casting Equipment





Continuous Casting Equipment



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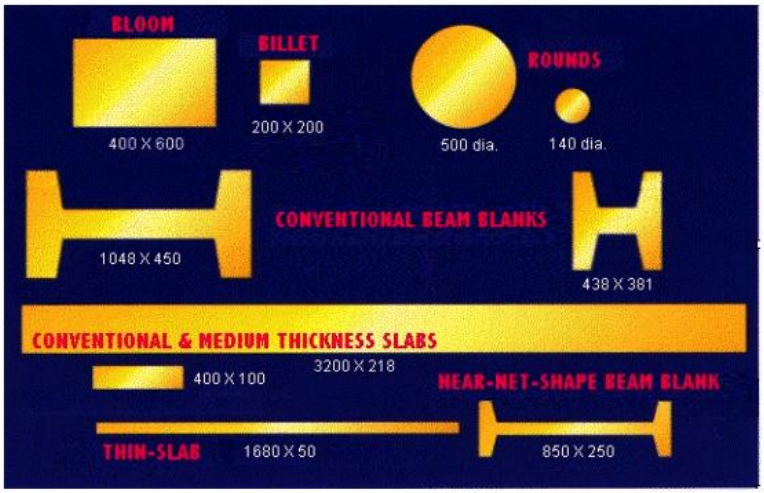
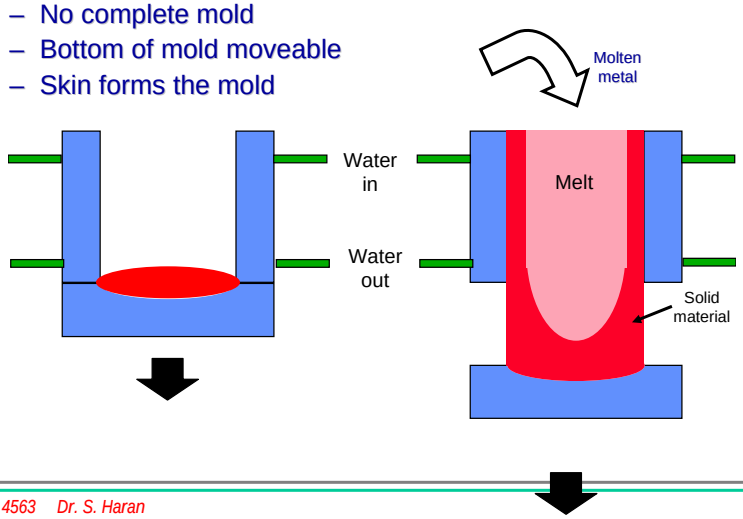
Continuous Casting Shapes



Dimensions in mm

Casting Process for Rolling & Extrusion

- Semi-continuous casting of ingot
  - No complete mold
  - Bottom of mold moveable
  - Skin forms the mold



Strip Casting (continuous)

- Thin slabs or strips are produced from molten metal
- Hot solid is often rolled to form final shape
- Rolling reduces porosity and provides better properties
- Eliminates a hot rolling operation in the production of metal strips and slabs
- Carbon steels, stainless steels, other metals & alloys

Net Shape Casting Processes

- Net Shape casting implies the direct casting of the metal into (or close to) the final desired shape
- Essentially what all the casting processes try to achieve

Net Shape Casting Processes

Casting Process
- Mold Materials
- Molding Process
- Method of feeding metal into the mold

- Casting
  - **Expendable Mold**
    - Permanent Pattern
    - Expendable Pattern
  - **Permanent Mold**

Net Shape Casting Processes

- Major Categories
  - Expendable mold
    - made of sand, plaster, ceramics with binders
    - mold broken up to remove cast shape
  - Permanent mold
    - used repeatedly
    - designed for ease of casting removal
    - typically fabricated of high temperature metals
    - typically provide higher quality castings because of the high rate of cooling
  - Composite mold
    - uses the advantages of both expendable and permanent molds

Expendable Molds Permanent Patterns

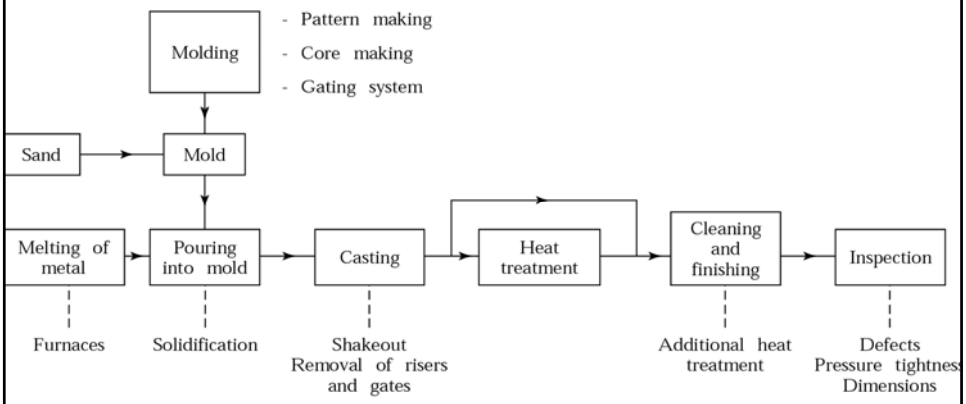
- Sand casting
- Shell-mold casting
- Plaster-mold casting
- Ceramic-mold casting
- Vacuum casting

Sand Casting

Sand Casting

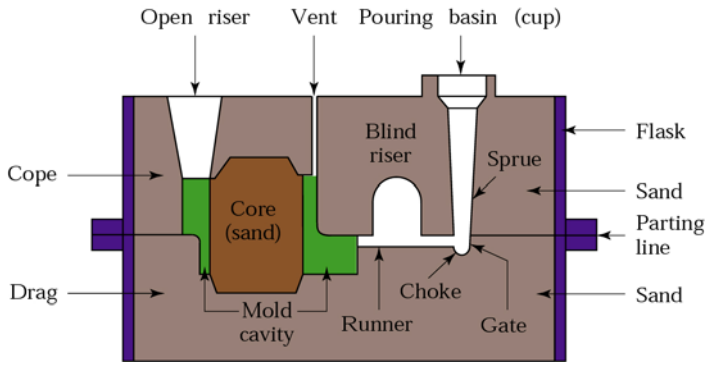
- Most ancient process
- Still most prevalent
- ~15 million tons produced each year
- Typical products include:
  - machine tool bases, engine blocks, cylinder heads, pump housings

Steps in Sand Casting



Outline of production steps in a typical sand-casting operation

Sand Mold Features



Schematic illustration of a sand mold, showing various features

Sand Casting

Sand casting consists of

- placing a pattern (having the shape of the desired casting) in sand to make an imprint,
- incorporating a gating system
- filling the resulting cavity with molten metal
- allowing the metal to cool until it solidifies
- breaking away the sand mold, and removing the casting

Sand casting is still the most prevalent form of casting. In the United States alone, about 15 million tons of metal are cast by this method each year.

Sand Casting

Advantages

- Least Expensive in small quantities (less than 100)
- Ferrous and non- ferrous metals may be cast
- Possible to cast very large parts.
- Least expensive tooling

Disadvantages

- Dimensional accuracy inferior to other processes, requires larger tolerances
- Castings usually exceed calculated weight
- Surface finish of ferrous castings usually poor

Sand Casting

Recommended

- Use when strength/weight ratio permits
- Tolerances, surface finish and low machining cost does not warrant a more expensive process

Sand Casting

Production (typical)

Batch Size: (total number of parts):
Low: 1-2
Just Right: 2-50,000
High: 50,000 to 200,000

Usual Production rate: 1-10 (parts per hour)
Usual Set-up Time: Days
(depends on the quantity)

Set-up Cost: Low (materials, etc.)
Cost per Part: High

Sand Casting

Geometry

Dimensional Tolerances (+/-0.001 inches per inch)
- Too Low: 20”
- Easily Achieved: on 32” or higher

Surface Roughness (micro-inches)
- Too Low: 20
- Easily Achieved: 500 or higher

Wall Thickness: Uniform Walls Preferred: Yes
- Max Wall Thickness (inches): 5
- Min Wall Thickness with 5 inch span (inches): 0.25

Rounded Corners Preferred: Yes

Sand Casting

Geometry

Compatible Shapes:

Typical parts made by sand casting are machine-tool bases, engine blocks, cylinder heads, bearing & pump housings, etc. Compatible shapes are of the following categories:

- Plane
- Prismatic
- Surface of Revolution
- Constant Cross Section
- Thin Wall

Sand Casting

Material Use

Most frequently used materials in sand casting are iron, carbon steel, alloy steel, stainless steel, aluminum alloys, brass, copper alloys, magnesium alloys and nickel alloys

Following is a table of materials and their "castability" ranking

A value of zero means that the corresponding material is never used with this process, a ranking of 100 means that it is excellent for use with this process.

Sand Casting

Cast Iron	100
Carbon Steel	100
Alloy Steel	100
Stainless Steel	100
Aluminum & Alloys	100
Copper & Alloys	100
Zinc & Alloys	80
Magnesium & Alloys	100
Titanium & Alloys	0
Nickel & Alloys	100
Refractory Metals	50
Thermoplastics	0
Thermosets	0
Ceramics	0
PhotoPolymers	0

Sand Casting

Basic steps in Sand Casting …

- Pattern Making
- Core Making
- Molding
- Metal is poured once the mold is ready
- Allowed to cool and removed

Sand Casting

Patternmaking

• The first step in sand casting is pattern-making.

• The pattern is a replica of the exterior of the casting with dimensional allocation for shrinkage and finishing.

• If the casting is to be hollow, additional patterns called cores are used to create these cavities in the finished product.

Sand Casting

Patternmaking

- Patterns are usually made of wood, plastic, metal, or plaster; however, other materials or combinations of materials are used if there are additional specific properties required of the pattern.

- The number of castings to be made from the mold and the specifications required of the finished casting are two of the criteria that determine which material is selected for the creation of the pattern.

Pattern Material Characteristics

TABLE 11.3

			Rating[a]		
Characteristic	*Wood*	*Aluminum*	*Steel*	*Plastic*	*Cast iron*
Machinability	E	G	F	G	G
Wear resistance	P	G	E	F	E
Strength	F	G	E	G	G
Weightb	E	G	P	G	P
Repairability	E	P	G	F	G
Resistance to:					
Corrosionc	E	E	P	E	P
Swellingc	P	E	E	E	E

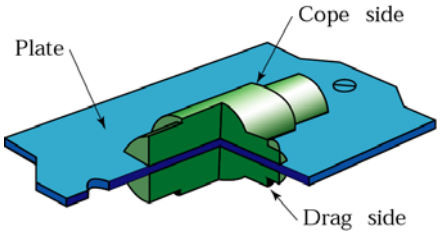
aE, Excellent; G, good; F, fair; P, poor.

bAs a factor in operator fatigue.

cBy water.

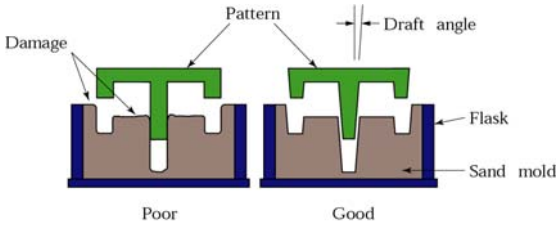
Source: D.C. Ekey and W.R. Winter, *Introduction to Foundry Technology.* New York. McGraw-Hill, 1958.

Patterns for Sand Casting



A typical metal match-plate pattern used in sand casting.

Taper on patterns for ease of removal from the sand mold



Sand Casting

Coremaking

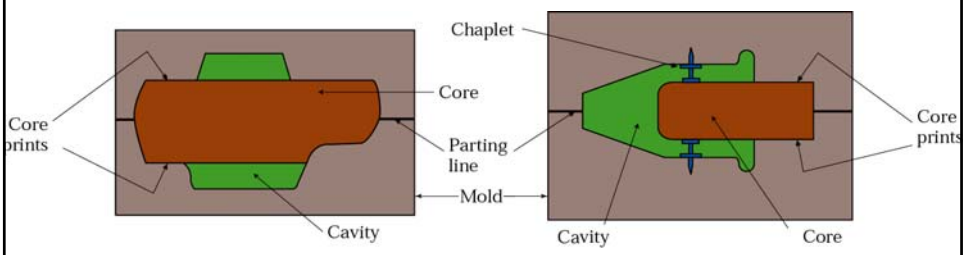
- The next step in the process is coremaking.
- Cores are forms which are placed into the mold to create the interior contours of the casting.
- They are typically made of a sand mixture- sand combined with water and organic adhesives called binders- which is baked to form the core.
- This allows the cores to be strong yet collapsible, so they can be easily removed from the finished casting.

Sand Casting

Coremaking

- Since cores are made in molds, they require a pattern and mold, called a core box.
- The core pattern is made in the same fashion as the casting pattern, but the core box is created from a durable material like metal or wood.
- Since the cores are made of sand, the mold cannot also be made of sand.

Examples of Sand Cores and Chaplets



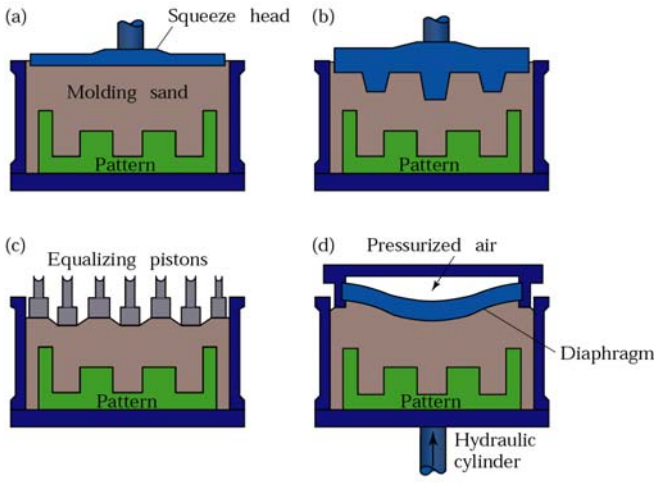
Examples of sand cores showing core prints and chaplets to support cores

Sand Casting

Molding

- Molding is the multi-step process in which molds are created
- In horizontal casting, the Mold is contained in a two piece frame, called a flask
- The upper portion of the flask is called a cope and the lower portion is a drag

Squeeze Heads



Various designs of squeeze heads for mold making: (a) conventional flat head; (b) profile head; (c) equalizing squeeze pistons; and (d) flexible diaphragm.

Source: © Institute of British Foundrymen.

Sand Casting

Molding

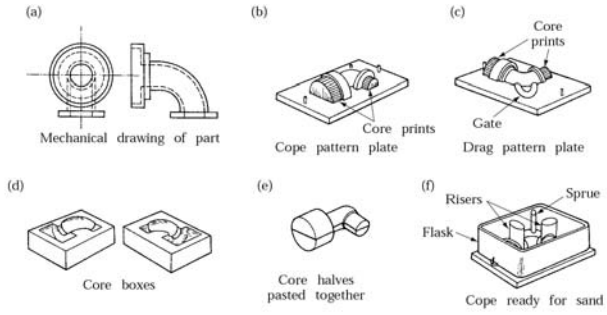
• First, molding sand is packed into a flask around the pattern. After the pattern is removed, gating and runner arrangements are positioned in the drag half of the mold cavity and the sprue is placed the cope portion.

• Gating systems are necessary for the molten metal to flow into the mold cavity.

• Cores are also placed in the drag portion of the mold if they are needed.

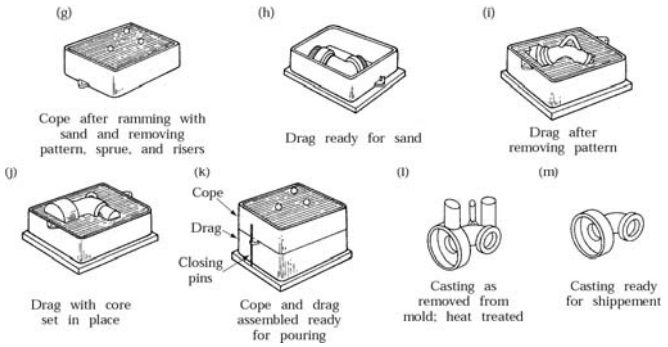
• To finish the mold, the cope (top) section is placed on the drag (bottom) section, and the mold is closed and clamped together.

Sequence of Operations for Sand Casting



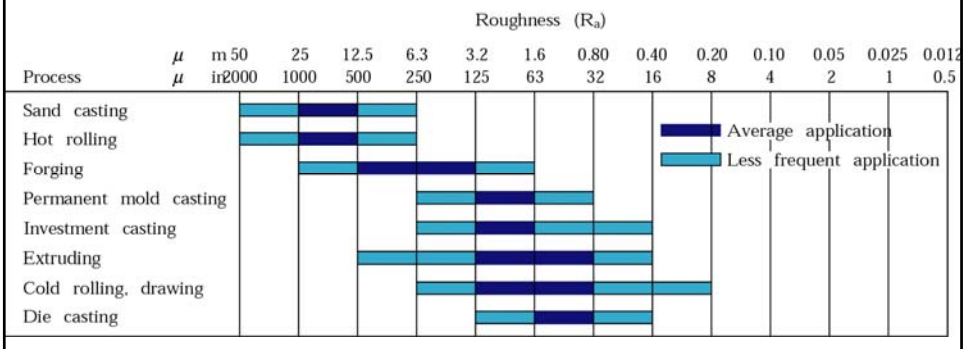
Schematic illustration of the sequence of operations for sand casting. *Source*: Steel Founders' Society of America. (a) A mechanical drawing of the part is used to generate a design for the pattern. Considerations such as part shrinkage and draft must be built into the drawing. (b-c) Patterns have been mounted on plates equipped with pins for alignment. Note the presence of core prints designed to hold the core in place. (d-e) Core boxes produce core halves, which are pasted together. The cores will be used to produce the hollow area of the part shown in (a). (f) The cope half of the mold is assembled by securing the cope pattern plate to the flask with aligning pins, and attaching inserts to form the sprue and risers. (continued)

Sequence of Operations for Sand Casting (cont.)



(g) The flask is rammed with sand and the plate and inserts are removed. (g) The drag half is produced in a similar manner, with the pattern inserted. A bottom board is placed below the drag and aligned with pins. (i) The pattern, flask, and bottom board are inverted, and the pattern is withdrawn, leaving the appropriate imprint. (j) The core is set in place within the drag cavity. (k) The mold is closed by placing the cope on top of the drag and buoyant forces in the liquid, which might lift the cope. (l) After the metal solidifies, the casting is removed from the mold. (m) The sprue and risers are cut off and recycled and the casting is cleaned, inspected, and heat treated (when necessary).

Surface Roughness for Various Metalworking Processes



Sand Casting – A Simple Example

The subject of the sand casting procedure below is a split pattern which forms half a hand-brake drum for a scale model steam truck

Sand Casting

1. On the left is the top (cope) and on the right is the bottom (drag) molding boxes.

2. The half-pattern is placed on the base plate ready to take the sand.

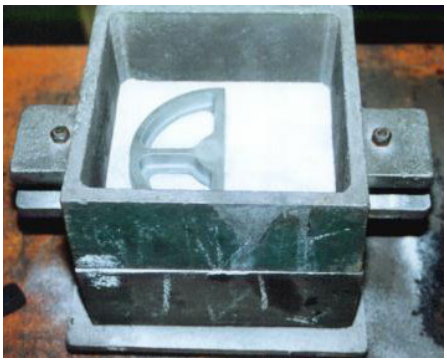
Sand Casting

3. The sand is tipped in the box and rammed down. The ramming tool is shown in front. The wedged end is used for the first ramming and the flat end is used on the second ramming.

4. Once the ramming is complete and the surface is leveled, the box is carefully turned over on its back.

   The exposed surface of the pattern is clearly shown

Sand Casting



5. The surface is dusted with parting powder and the other half of the pattern is placed on the first half still embedded in the sand. The top box is placed on the bottom box and skewed clockwise against the registration pegs.

Sand Casting

6. The runner (right tube) is pushed into the sand in the bottom box and the riser (left tube) is placed onto the pattern hub.

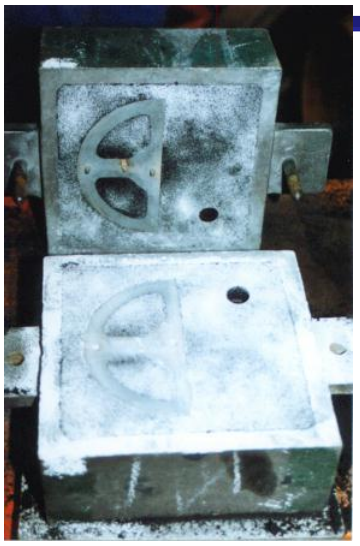
The tubes are held in place while the sand is shoveled in.

Sand Casting

7. The sand is rammed down and leveled off. The runner basin is cut into the top surface of the sand at this stage.

The boxes can now be separated (very carefully).

Sand Casting



8. The box halves with the pattern still in place.

   The white surface is the parting powder (talc).

   The small hole in the sand is the well left by the runner tube.

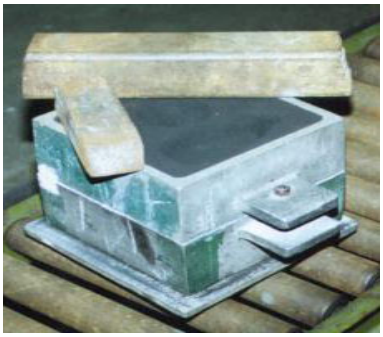
Sand Casting

9. The pattern is removed by lightly tapping it.

   The runner bar with its extension and the ingate is cut into the sand surface and smoothed off.

   At this stage the boxes are put back together.

Sand Casting



10. The completed mould ready to pour in the molten cast iron.

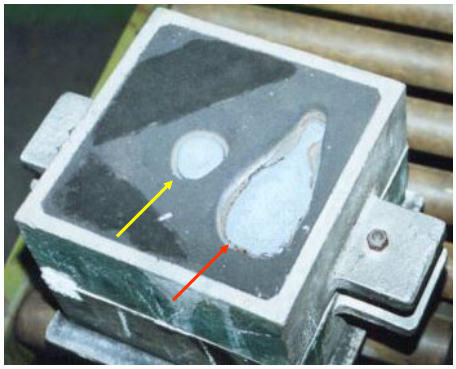
    The iron weights help keep the boxes together during the pouring process.

Sand Casting

11. The molten cast iron being poured into the mould.

    The slag is kept away from the pouring lip.

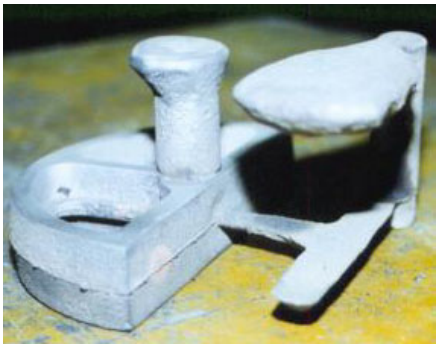
Sand Casting



12. The metal has cooled.

    Note the runner basin on the right and the riser opening to the left.

Sand Casting



13. The casting is removed from the sand and looks like this.

    The riser and sprue are cut off the main casting.

Sand Casting – In Industry

So, in practice …

Molds are made in sand, using wood patterns

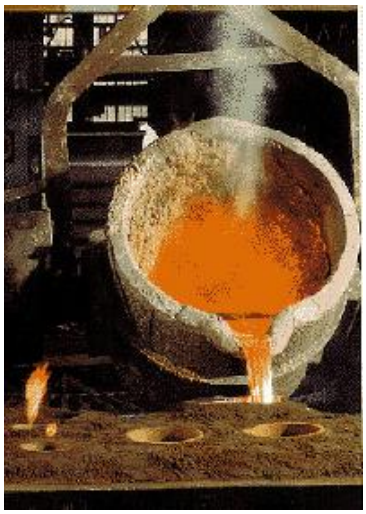
Sand Casting

Tempered sand is packed onto wood or metal pattern halves, removed from the pattern, and assembled with or without cores, and metal is poured into resultant cavities.

Various core materials can be used.

Molds are broken to remove castings.

Specialized binders now in use can improve tolerances and surface finish.



Sand Casting

Metal is heated in the furnace, which reaches 2,500F degrees

Sand Casting

Hot metal is poured into the molds

Sand Casting

Pouring the melted metal in the sand molds

Sand Casting

The metal cools in the molds...

And is eventually removed

Sand Casting

Allowance on Patterns

- SHRINKAGE
  - cast iron 0.8 - 1.0 %
  - steel 1.5 - 2.0 %
  - Al 1.0 - 1.3 %
  - Mg 1.0 - 1.3 %
  - brass 1.5 %
- FINISH ALLOWANCE FOR MACHINING
- DISTORTION ALLOWANCE (FROM EXPERIENCE)

Sand Casting

Sand Requirements

- REFRACTORINESS - withstand high temperature without fusing; adversely affected by impurities
- STRENGTH - ability to retain shape when packed in a mould
  - green strength (after pattern removed)
  - dry strength (after dried or gasses)

Sand Casting

Sand Requirements

- PERMEABILITY - allow escape of gas, function of sand particle size, bonding agent and moisture
- COLLAPSIBILITY - ability to permit metal to shrink after solidification, obtained by adding organic materials such as cellulose which burn out when exposed to hot metal

Sand Casting

Factors Affecting Sand Properties

- grain size / shape
- type / amount of bonding agent
- moisture content
- impurities
- typical foundry sand constitutes :
  - quartz 80 - 90 %
  - clay substance 4 - 15 %
  - moisture 3 - 7 %
  - impurities 3 - 6 %

Sand Casting

CO_2 Sand

$$Na_2SiO_3 + CO_2 \text{ --> } Na_2CO_3 + SiO_2$$

- ADVANTAGES
  - non toxic
  - no heating required
- DISADVANTAGES
  - when hardened, poor collapsibility - difficult to shake out
  - heating during pour makes the sand even stronger, further reduces collapsibility

Sand Casting

Sand Testing

- moisture test
- green strength
- permeability
- loss on ignition (5 gm of sand placed in oven at 920^{o}C for 2 hours)
- active clay content
- shatter test - toughness of sand under impact
- sieve test - range of sand grain size

Shell Mold Casting Process

Shell Mold Casting

What is it ?

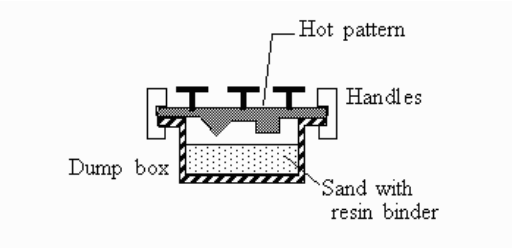
- Resin-coated sand is poured onto hot metal patterns, curing into shell-like mold halves.
- These are removed from the pattern and assembled with or without cores. Metal is poured into resultant cavities.
- Molds are broken to remove castings

Shell Mold Casting

The use of *shell-mold casting* has grown significantly, because it can produce many types of castings with close tolerances and good surface finishes at a low cost

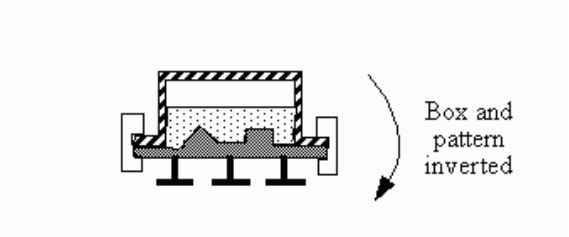
Shell Molding can be thought of as a special kind of sand casting where the sand has been mixed with a thermosetting plastic. This plastic when heated bonds the particles of sand together

Shell Mold Fabrication



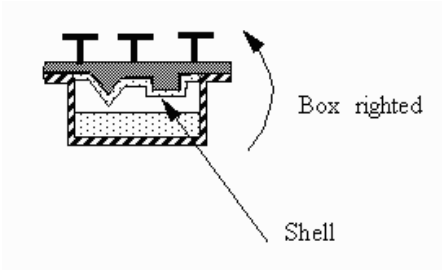
- A Mounted pattern made of ferrous or aluminum is heated to 175-370 deg C
- Coated with a “parting agent” such as silicone
- Heated pattern placed over a dump box containing a sand and resin mixture and clamped

Shell Mold Fabrication



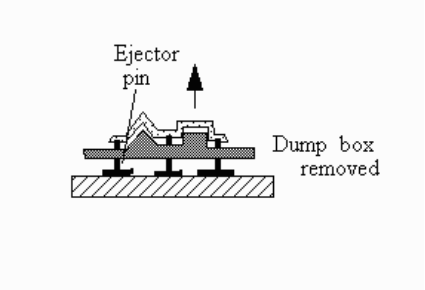
- The box contains fine sand mixed with 2.5-4% thermosetting resin binder
- The binder coats the sand particles
- The box is inverted and the sand coats the pattern
- A shell partially cures around the pattern

Shell Mold Fabrication



- The assembly may be placed in an oven for the resin to cure
- The box is then turned upright

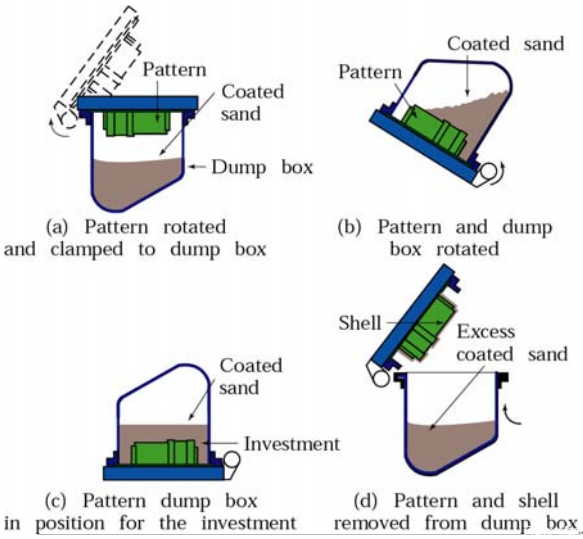
Shell Mold Fabrication



The top is removed and the shell is further cured and is finally stripped from the pattern using ejector pins

Once the shells are formed, two matched shells are joined and supported in a flask ready for pouring

Dump-Box Technique



A common method of making shell molds. Called *dump-box* technique, the limitations are the formation of voids in the shell and peel-back (when sections of the shell fall off as the pattern is raised). *Source*: ASM International.

Shell Mold Casting

Properties of a Shell Mold

- The shells are light and thin, usually 5-10 mm, and consequently their thermal characteristics are different from those for thicker molds.

- The mold is generally used vertically and is supported by surrounding it with steel shot in a cart.

- The walls of the mold are relatively smooth, offering low resistance to flow of the molten metal and producing castings with sharp corners, thinner sections, and smaller projections than are possible in green-sand molds.

- With the use of multiple gating systems, several castings can be made in a single mold.

Shell Mold Casting

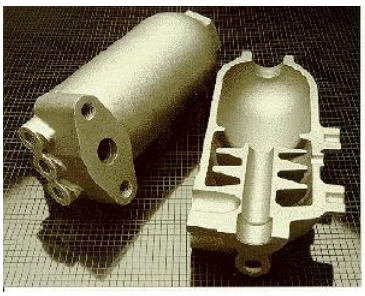
Batch Size (total number of parts):
- Low: 500 - 1000
- Just Right: 1000 - 100,000
- High: 100,000 - 200,000

Usual Production rate: 1-10 (parts per hour)
Usual Setup Time: Weeks

Setup Cost: Medium
Per Part Cost: Medium

Shell Mold Casting

Example of the complexity of the shapes that can be produced in Shell Mold Casting



Shell Mold Casting

Advantages:

- Shell-mold casting may be more economical than other casting processes, depending on various production factors, particularly energy cost.
- The relatively high cost of metal patterns becomes a smaller factor as the size of production run increases.
- The high quality of the finished casting can significantly reduce cleaning, machining, and other finishing costs.
- It has the best product accuracy of all the sand-casting methods. It can produce small, complicated parts where accuracy is important.
- The sand to metal ratio is low.
- The molds produced are lightweight. They are readily handled and have good storage characteristics.

Shell Mold Casting

Disadvantages:

- The process generates noxious fumes which must be effectively extracted
- Equipment and tooling require a large investment. The raw materials are relatively expensive
- The size and weight range of castings is limited

Use of COMPOSITE Molds:

- Mold is made of two or more materials
- For casting complex shapes
- Common materials – plaster, sand with binding agent, graphite and metal
- Increased strength, better dimensional accuracy and surface finish for castings

Plaster Mold Casting

- In this process the mold is made of plaster of paris instead of sand
- The rest of the process is similar to sand casting in that the two halves of the mold are clamped together and the molten metal poured in
- Often referred to as "precision casting" because of the finer details and dimensional accuracy that can be obtained

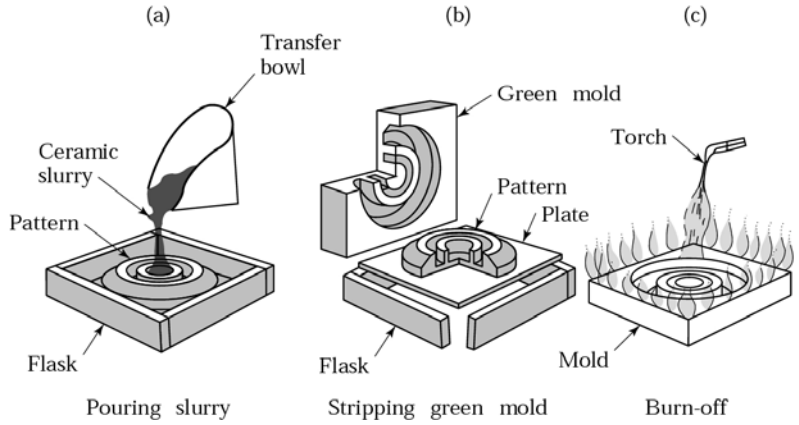
Plaster Mold Casting

- Advantages
  - Slower cooling gives a more uniform grain structure and less warpage
  - Can produce casting with fine details and good surface finish
  - Casting can have wall thickness as low as 1 mm
  - Casting has high dimensional accuracy
- Disadvantages
  - Can only be used for Aluminum, Magnesium, zinc and some copper based alloys because of the max temperature capability of the mold
  - Low mold permeability – controlled atmosphere

Ceramic Mold Casting

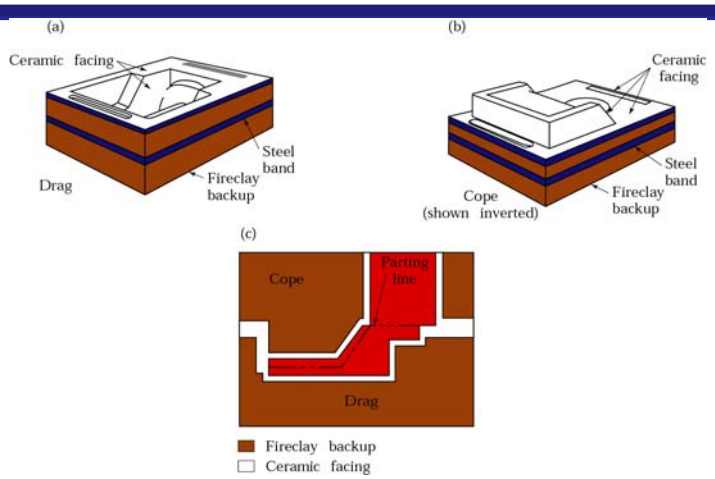
- Again, a “precision casting” process
- In this process the mold is made of ceramic and other refractory materials for high temperature applications
- Slurry is a mixture of Zircon ($ZrSiO_4$), Al Oxide and fused silica, mixed with bonding agents and poured over the pattern
- Pattern can be wooden or metallic
- After setting, mold is removed, dried, burned off to remove volatile matter and then baked
- Molds are then used in the casting process
- Used for high temp. alloys, stainless steel and tool steel; good finish, intricate shapes (Impellers, machine tool components..)
- Molds for other components (plastic or rubber) made by this process
- Somewhat expensive

Ceramic Molds



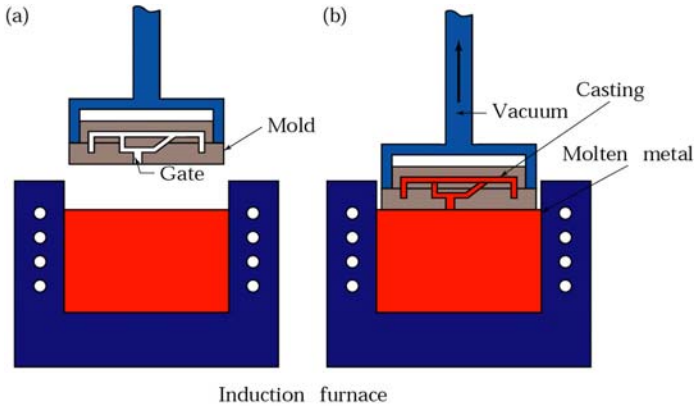
Sequence of operations in making a ceramic mold. *Source*: *Metals Handbook*, vol. 5, 8th ed.

Ceramic Molds



A typical ceramic mold (Shaw process) for casting steel dies used in hot forging. *Source: Metals Handbook*, vol. 5, 8th ed.

Vacuum-Casting Process



Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) Before and (b) after immersion of the mold into the molten metal. *Source*: From R. Blackburn, "Vacuum Casting Goes Commercial," *Advanced Materials and Processes*, February 1990, p. 18. ASM International.

Other forms of Casting

- Plastics
  - solidification occurs by a reaction
    - with added hardener/activator
    - with moisture in the air
- Ceramics
  - Like molten metals but at much higher temperatures
    - Only simple shapes possible
  - Slurry casting
    - Powder ceramic mixed with water to form a fluid which is poured into the mold
    - Mold is porous and extracts the water
    - Cast body must be dried and fired at high temperatures to obtain reasonable strength

Expendable Molds
Expendable Patterns

- Evaporative pattern casting (lost foam)
- Investment casting (lost wax)

Investment Casting

Investment Casting Process

- **Investment casting** is also known as the Lost Wax Process. This process is one of the oldest manufacturing processes
- The Egyptians used it in the time of the Pharaohs to make gold jewelry (hence the name Investment) some 5,000 years ago. Intricate shapes can be made with high accuracy
- In addition, metals that are hard to machine or fabricate are good candidates for this process
- It can be used to make parts that cannot be produced by normal manufacturing techniques, such as turbine blades that have complex shapes, or airplane parts that have to withstand high temperatures

Investment Casting Process

History

Ancient Egyptian investment castings from the tomb of Tut-Ankh-Amun.

Investment Casting Process

- The types of materials that can be cast are Aluminum alloys, Bronzes, tool steels, stainless steels, Stellite, Hastelloys, and precious metals.

- Parts made with investment castings often do not require any further machining, because of the close tolerances that can be achieved.

Investment Casting Process

- Tolerances of 0.5 % of length are routinely possible, and as low as 0.15 % is possible for small dimensions

- Castings can weigh from a few grams to 35 kg (0.1 oz to 80 lb), although the normal size ranges from 200 g to about 8 kg (7 oz to 15 lb)

- Normal minimum wall thickness is about 1 mm to about 0.5 mm (0.040-0.020 in) for alloys that can be cast easily

Why Investment Casting ?

DESIGN FLEXIBILITY

Investment casting produces near-net-shape configurations, offering designers and engineers freedom of design in a wide range of alloys. The process is capable of producing precise detail and dimensional accuracy in parts weighing many pounds or just a few ounces.

WIDE CHOICE OF ALLOYS

More than 120 ferrous and nonferrous metals are routinely cast

ELIMINATE TOOLING SET-UP

By offering near-net-shape configuration, fixturing costs are substantially reduced or eliminated.

Hitchener Manufacturing Co., Inc., Milford, New Hampshire

Why Investment Casting ?

REDUCE PRODUCTION COSTS

Costly machining operations are reduced and often eliminated. No capital equipment investment is needed to produce parts in-house.

CUT ASSEMBLY OPERATIONS

Several parts can be made as one casting, reducing handling, assembly and inspection costs.

REPRODUCE FINE DETAILS

Splines, holes, bosses, lettering, serrations and even some threads can be cast.

Hitchener Manufacturing Co., Inc., Milford, New Hampshire

Investment Casting

Advantages

- Close dimensional tolerance
- Complex shape, fine detail, intricate core sections and thin walls are possible
- Ferrous and non-ferrous metals may be cast
- "As-Cast" finish

Disadvantages

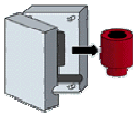
- Costs are higher than Sand, Permanent Mold or Plaster process castings

Investment Casting

Recommended

- Use when complexity precludes use of Sand or Permanent Mold Castings
- The process cost is justified through savings in machining or brazing
- Weight savings justifies increased cost

Investment Casting Process



1. WAX INJECTION

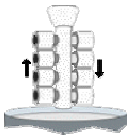
Wax replicas of the desired castings are produced by injection molding. These replicas are called patterns.

2. ASSEMBLY

The patterns are attached to a central wax stick, called a sprue, to form a casting cluster or assembly.

Hitchener Manufacturing Co., Inc., Milford, New Hampshire

Investment Casting Process



3. SHELL BUILDING

The shell is built by immersing the assembly in a liquid ceramic slurry and then into a bed of extremely fine sand. Up to eight layers may be applied in this manner.

4. DEWAX

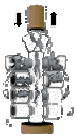
Once the ceramic is dry, the wax is melted out, creating a negative impression of the assembly within the shell.

Hitchener Manufacturing Co., Inc., Milford, New Hampshire

Investment Casting Process

5. CONVENTIONAL CASTING

In the conventional process, the shell is filled with molten metal by gravity pouring. As the metal cools, the parts and gates, sprue and pouring cup become one solid casting.



6. KNOCKOUT

When the metal has cooled and solidified, the ceramic shell is broken off by vibration or water blasting.

Investment Casting Process

7. CUT OFF

The parts are cut away from the central sprue using a high speed friction saw.

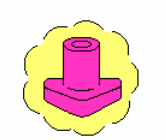
8. FINISHED CASTINGS

After minor finishing operations, the metal castings--identical to the original wax patterns--are ready for shipment to the customer.

Investment Casting Process

9. Shell Removal and Heat Treatment

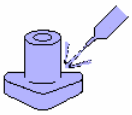
The shell is broken and removed; the product undergoes heat treatment to control hardness and properties.



10. Finishing

Finally, the product is sand-blasted to get a smooth and attractive finish.

- Different processes are used according to material and quality requirements.



Investment Casting Process

11. Testing and Inspection

Products are subject to external and internal inspections, appearance, dimensional and gauge checks over the surface and X-ray inspection, respectively.

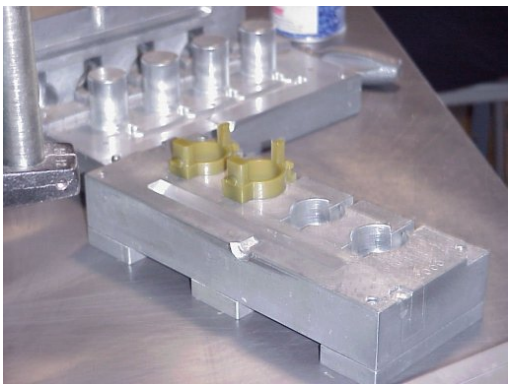
Investment Casting Process – In Industry

Pattern Production

A pattern is made by injecting wax into the metal die.

The patterns have the exact geometry of the required finished casting

Investment Casting Process – In Industry



Pattern Production

The process begins with production of a one piece pattern.

This pattern is usually made by injecting wax into an aluminum die.

Investment Casting Process – In Industry

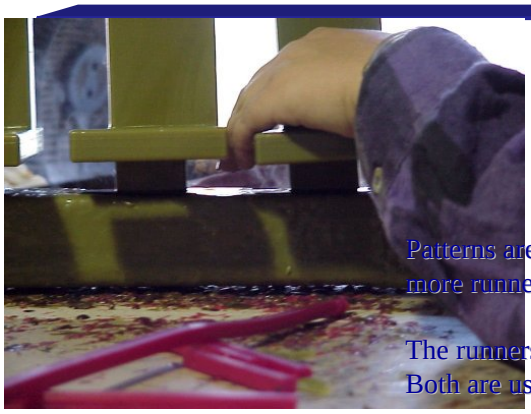
Pattern Assembly

Wax patterns are removed from the die and assembled to a wax gating system.

The gating system serves as a conduit for molten metal to quickly fill the mold.

The gating runner system is attached to a pour cup to comprise a complete wax pattern assembly.

Investment Casting Process – In Industry



Pattern Assembly

Patterns are fastened by the gates to one or more runners.

The runners are attached to the pouring cup. Both are usually made of wax.

Patterns, runners and pouring cup comprise the cluster or tree, which is needed to produce the ceramic mold.

Investment Casting Process – In Industry

Ceramic Shell Molding

Assembled wax patterns are dipped into a ceramic slurry, drained, then coated with fine ceramic sand.

After drying, this process is repeated several times using progressively coarser grades of ceramic material, until a strengthened shell has been formed.

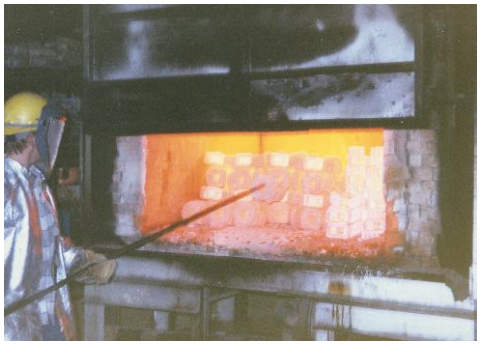
Investment Casting Process – In Industry

Ceramic Shell De-waxing

The coated cluster is placed in a high temperature furnace or steam autoclave.

This melts out the patterns, gates, runners and pouring cup - creating a ceramic shell containing cavities of the casting shape desired with passages leading to them.

Investment Casting Process – In Industry



Ceramic Shell Firing

The molds must be fired to burn out the last traces of pattern material and remove any moisture, bring the shell to fired strength and aid in fluidity for thin sections

Investment Casting Process – In Industry

Casting

Ceramic shell molds are preheated then filled with molten metal alloy for solidification in the shell.

Investment Casting Process – In Industry

Casting

Molten Metal is poured into the fired shell at temperatures between 1300°F - 2950°F depending on the type of alloy. Pouring temperatures are maintained as cool as possible.

Investment Casting Process – In Industry

Mold Removal

After the poured metal has cooled, the mold material is removed from the casting cluster.

Using high pressure water, vibratory or shot blast methods

Investment Casting Process – In Industry

Casting Cut off and Clean-Up/Finishing

The individual castings are removed from the cluster

Remaining protrusions left by gates or runners are removed by radial or frictional saws.

Generally the castings are sand blasted for a smoother finish.

Investment Casting Process

Process Characteristics

- **FREEDOM OF DESIGN**
- **HIGH PRODUCTION RATES**
- **HIGH DIMENSIONAL ACCURACY**
- **HIGH DIMENSIONAL CONSISTENCY**
- **HIGH INTEGRITY CASTINGS**
- **EXTREMELY GOOD SURFACE FINISH CAN BE OBTAINED**
- **COMPLEX SHAPES CAN BE CAST**
- **LONG/SHORT RUNS CAN BE ACCOMMODATED**
- **MACHINING CAN BE REDUCED OR ELIMINATED**
- **MINIMUM FINISHING OF CASTINGS REQUIRED**
- **ALMOST ANY ALLOY CAN BE CAST**
- **ENVIRONMENTALLY FRIENDLY PROCESS**

Investment Casting Process

Because the mold is formed around a one-piece pattern, (which does not have to be pulled out from the mold as in a traditional sand casting process), very intricate parts and undercuts can be made.

The wax pattern itself is made by duplicating using a stereo-lithography or similar model - which has been fabricated using a computer solid model master.

Investment Casting Process

- The materials used for the slurry are a mixture of plaster of Paris, a binder and powdered silica, a refractory, for low temperature melts
- For higher temperature melts, sillimanite an alumina-silicate is used as a refractory, and silica is used as a binder
- Depending on the fineness of the finish desired additional coatings of sillimanite and ethyl silicate may be applied
- The mold thus produced can be used directly for light castings, or be reinforced by placing it in a larger container and reinforcing it more slurry

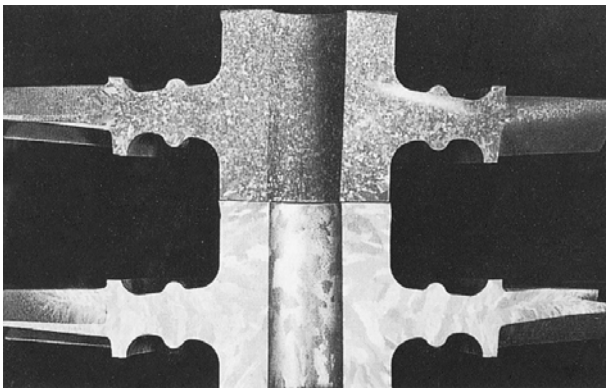
Investment Casting Process

- Just before the pour, the mold is pre-heated to about 1000 °C (1832 °F) to remove any residues of wax, harden the binder
- The pour in the pre-heated mold also ensures that the mold will fill completely
- Pouring can be done using gravity, pressure or vacuum conditions
- Attention must be paid to mold permeability when using pressure, to allow the air to escape as the pour is done

Investment Casting of a Rotor

Investment casting of an integrally cast rotor for a gas turbine. (a) Wax pattern assembly. (b) Ceramic shell around wax pattern. (c) Wax is melted out and the mold is filled, under a vacuum, with molten superalloy. (d) The cast rotor, produced to net or near-net shape. *Source*: Howmet Corporation.

Investment and Conventionally Cast Rotors



Cross-section and microstructure of two rotors: (top) investment-cast; (bottom) conventionally cast. *Source*: *Advanced Materials and Processes*, October 1990, p. 25 ASM International

Investment Casting Process

Hand Tools

Door Hardware

OEM Components

Valve & Instrumentation

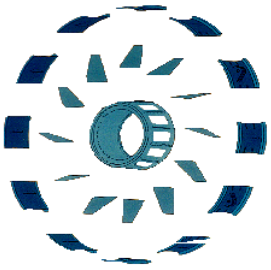
Oil Field & Mechanical Seal

Investment Casting Process

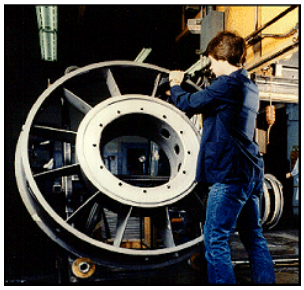
Investment Casting is a manufacturing method for alloy based parts of the aerospace, gas turbine, medical, general industrial, and other commercial applications in which the advantages of the process are numerous.

The principal advantage over other processes such as fabrication, forging and extrusion is the production of a single, complex, near-net shape casting.

Investment Casting Process



Exploded View of Turbine Rear Frame where 39 individual pieces are welded together in fabrication of a CF6-80A Turbine Rear Frame



One Piece Cast Turbine Rear Frame

Investment Casting Process

In contrast, this one-piece casting of the frame not only saved considerable weld-prep time and eliminated nearly 1000 inches (25,400 mm) of assembly welding, the process also allowed the design engineer to reduce the end weight of the frame by 12 pounds (5.45 kg).

Parts that are impractical to machine or too complex or costly to fabricate from sheet metal and extrusions are often easily cast. Casting Technology yields a flexible part design that has more efficient stress distribution, significantly lower stress values, and a possible increase in service life.

PCC Structurals Inc., Portland, OR, USA

Lost Foam Process

- The pattern is formed from polystyrene and the sand is formed around it.
- On pouring the molten metal into the mold, the polystyrene evaporates and is replaced by the melt
- It is probably one of the most important process for the ferrous and non-ferrous metals industry
  - Particularly important for the automotive industry.

Lost Foam Process

- Advantages
  - A relatively simple process
  - No parting lines
  - Flasks or containers can be inexpensive
  - Requires minimal finishing operations
  - Can be automated
  - Can be used for long production runs
  - Complex patterns may be made by bonding polystyrene components together
- Disadvantages
  - Fluidity is lower than in conventional sand casting because of large temperature gradients

Permanent Molds

- Die casting
- Centrifugal casting
- Squeeze casting
- Casting of Single Crystals

Permanent Mold Casting

- Molds made in two halves from cast iron, steel, bronze, graphite or refractory hard alloys
- Surfaces coated with refractories to increase die life, control heat transfer and help separate casting from mold

Kalpakjian Ch 11.9

Permanent Mold Casting

- Advantages
  - Good surface finish
  - Close tolerances
  - Uniform mechanical properties
  - Fine details
  - Thin walls
  - High production rates
  - Automated version have low labor costs
  - Large size range (few gms to >=100kgs)
- Disadvantages
  - High equipment costs
  - Not economical for small production lots
  - Cannot do intricate shapes

Types of Permanent Mold

- Gravity feed
- Pressure-casting
  - Die casting
    - Hot chambers
  - Cold chambers
  - Insert molding (cast in place inserts)
  - Centrifugal Casting
  - Squeeze casting
  - Semisolid metal working (forging in the slushy state)

Die Casting Process

Die Casting Process

- Die casting is a manufacturing process for producing accurately dimensioned, sharply defined metal parts: typically castable alloys of aluminum, zinc or magnesium.

- It is usually accomplished by forcing molten metal under high pressure into reusable metal dies.

Die Casting

- Advantages
  - Multiple dies allow higher production rates
  - Thin wall, intricate parts, complex shapes
  - Fine surface detail possible
  - High production rates with automated machines
  - Inserts such as fasteners may be die cast integrally
  - Good dimensional accuracy, closer tolerances
  - Fine grained, high strength skin results

Die Casting Process

Disadvantages

- Economical only in very large quantities due to high tooling cost
- Not recommended for hydrostatic pressure applications
- For Castings where dye penetrant or radiographic inspection are not required
- Difficult to guarantee minimum mechanical properties

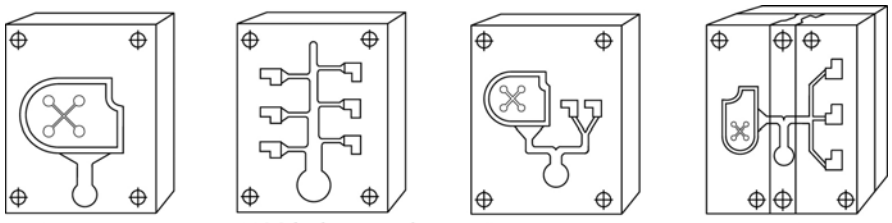
Die Casting Process

TYPES OF DIES

- A single cavity die requires no explanation.
- Multiple cavity dies have several cavities which are all identical.
- If a die has cavities of different shapes, it's called a combination or family die. A combination die is used to produce several parts for an assembly
- For simple parts, unit dies might be used to effect tooling and production economies.
- Several parts for an assembly, or for different customers, might be cast at the same time with unit dies. One or more unit dies are assembled in a common holder and connected by runners to a common opening or sprue hole. This permits simultaneous filling of all cavities

Die Casting Process

TYPES OF DIES

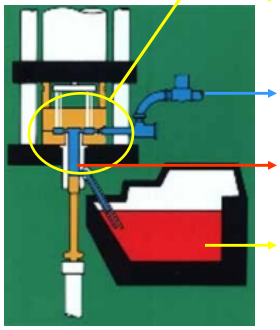


(a) Single-cavity die (b) Multiple-cavity die (c) Combination die (d) Unit die

Die Casting Process

- Die-casting is similar to permanent mold casting, except that the metal is injected into the mold under *high pressure* of 10-210Mpa (1,450-30,500) psi.
- This results in a more uniform part, generally good surface finish and good dimensional accuracy, as good as 0.2 % of casting dimension
- For many parts, *post-machining can be totally eliminated*, or very light machining may be required to bring dimensions to size

Die Casting Process



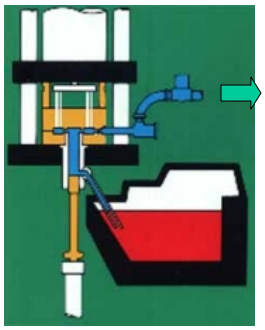
The Die Casting chamber where the Die resides

Vacuum System

Metal Injection Cylinder

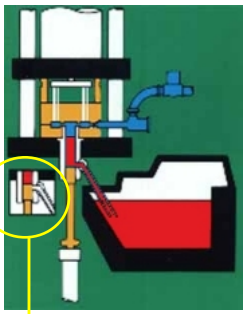
Molten Metal

Die Casting Process



A strong vacuum instantaneously evacuates all air from the cavities and feed channels.

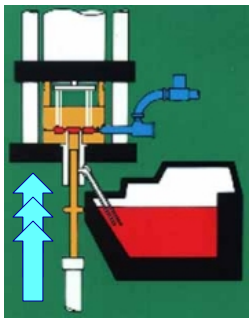
Die Casting Process



Transfer Tube

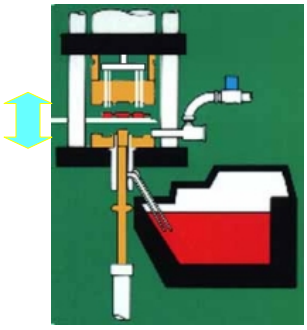
- In two seconds or less, the desired amount of molten alloy is drawn from the center of the melt, through the transfer tube, and into the injection cylinder.
- The first movement of the plunger shuts off the metal flow from the feed tube to control the amount of metal ladled.

Die Casting Process



The molten alloy is then smoothly injected into the air-free die cavities and high pressure is brought to bear on the freezing metal, while the vacuum remains active

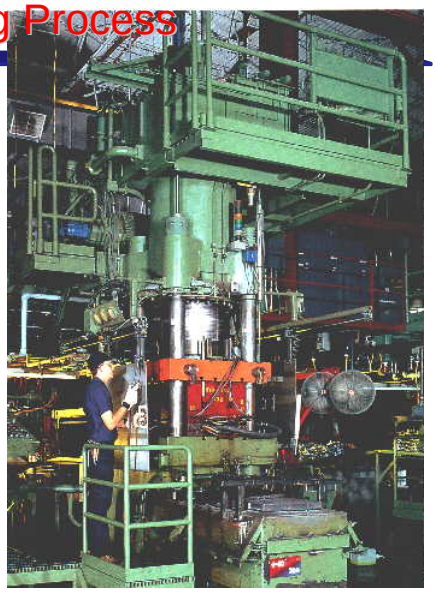
Die Casting Process



After a dwell time, the die opens and the part is automatically ejected onto a shuttle tray for transfer out of the die area

Die Casting Process

Die Casting Machine



Die Casting Process

Die-casting can be achieved the following different ways

- Cold Chamber Process
- Hot Chamber Process
- Low Pressure Die Casting
- Squeeze Die Casting
- Gravity or Permanent Mold Die Casting

Die Casting Process

- In a *cold chamber process*, the molten metal is ladled into the cold chamber for each shot
- There is less time exposure of the melt to the plunger walls or the plunger
- This is particularly useful for metals such as Aluminum, and Copper (and its alloys) that alloy easily with Iron at the higher temperatures

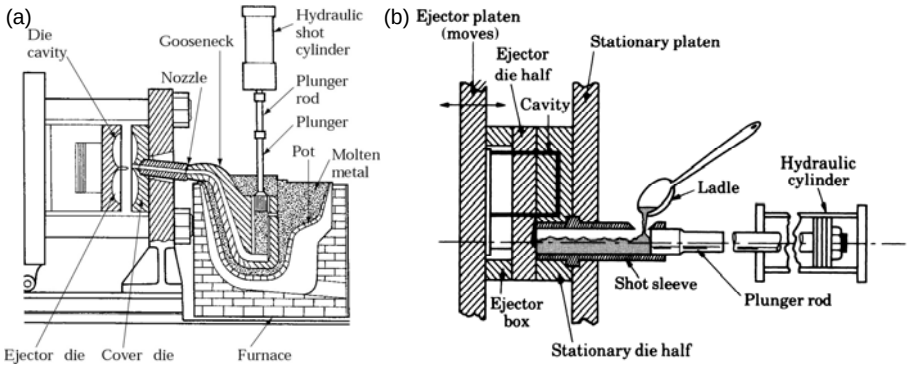
Die Casting Process

- In a *hot chamber process* the pressure chamber is connected to the die cavity is immersed permanently in the molten metal.

- The inlet port of the pressurizing cylinder is uncovered as the plunger moves to the open (un-pressurized) position. This allows a new charge of molten metal to fill the cavity and thus can fill the cavity faster than the cold chamber process.

- The hot chamber process is used for metals of low melting point and high fluidity such as tin, zinc, and lead that tend not to alloy easily with steel at their melt temperatures.

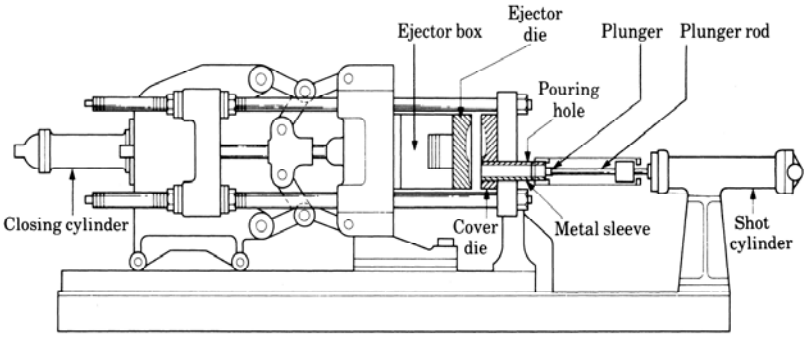
Die Casting Process



(a) Schematic illustration of the hot-chamber die-casting process. (b) Schematic illustration of the cold-chamber die-casting process. *Source*: Courtesy of *Foundry Management and Technology*.

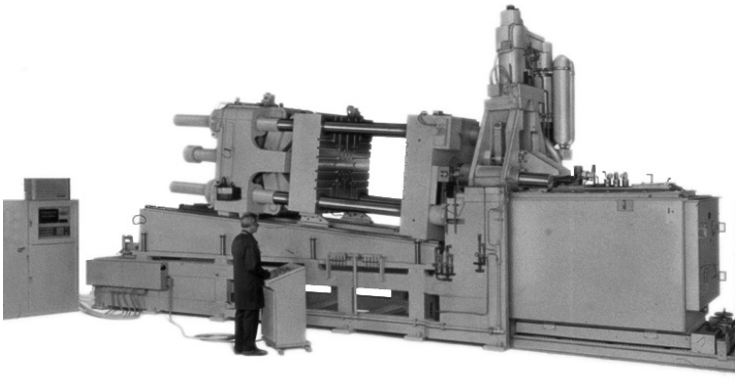
Cold Chamber Die Casting

(a)



Hot Chamber Die Casting

(b)



Die Casting Process

Low Pressure Die Casting

Molten metal is introduced into a die from below by means of a low pressure gas applied to the metal in a sealed furnace. Used for high integrity aluminum castings such as automotive wheels.

Squeeze Casting

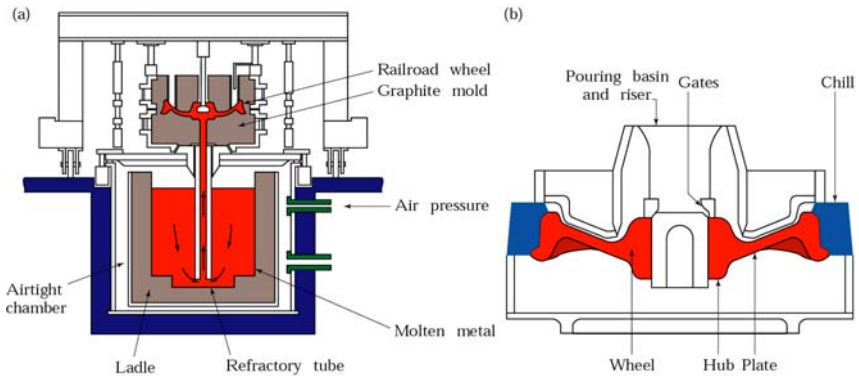
Molten metal is introduced very slowly and smoothly into a die where high pressure is maintained until after the casting is solid. Used for high integrity, high strength aluminum castings such as automotive brake callipers.

Die Casting Process

Gravity or Permanent Mould Die Casting

The molten metal is gently poured into the die cavity under the force of gravity. Used for all alloys, particularly large aluminum castings and those requiring sand cores for complex internal detail, such as automotive cylinder heads.

Die Casting – Pressure & Gravity



Die Casting Process

- Die casting molds (called dies in the industry) tend to be expensive as they are made from hardened steel-also the cycle time for building these tend to be long.
- Also the stronger and harder metals such as iron and steel cannot be die-cast
- *Aluminum*, *Zinc* and *Copper alloys* are the materials predominantly used in die-casting

Die Casting Process

- Die-castings are typically limited from 20 kg (55 lb) max. for Magnesium, to 35 kg (77 lb) max. for Zinc
- Large castings tend to have greater porosity problems, due to entrapped air, and the melt solidifying before it gets to the furthest extremities of the die-cast cavity
- The porosity problem can be somewhat overcome by vacuum die casting

Die Casting Process

- From a design point of view, it is best to design parts with uniform wall thickness and cores of simple shapes. Heavy sections cause cooling problems, trapped gases causing porosity.
- All corners should be radius-ed generously to avoid stress concentration.
- Draft allowance should be provided to all for releasing the parts-these are typically 0.25º to 0.75º per side depending on the material.

Automation in Die Casting Process

- A die caster progresses towards automation by mechanizing various steps of the die casting process. For example:
- Die lubrication can be accomplished by installing fixed or reciprocating spray systems
- An automatic ladling device can replace the hand ladle
- Castings can be removed from the die by extractors or robots, or by "drop through" to a conveyor below the machine
- Die casting machine operation can be integrated to cast, quench, trim and eject castings and return scrap to the furnace by conveyor

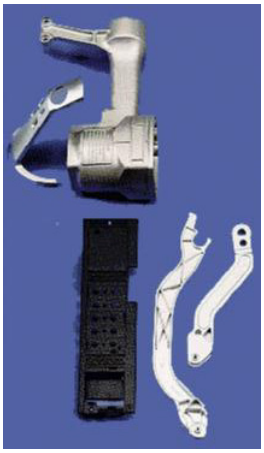
Properties and Typical Applications of Common Die-Casting Alloys

TABLE 11.4

Alloy	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Applications
Aluminum 380 (3.5 Cu-8.5 Si)	320	160	2.5	Appliances, automotive components, electrical motor frames and housings
13 (12 Si)	300	150	2.5	Complex shapes with thin walls, parts requiring strength at elevated temperatures
Brass 858 (60 Cu)	380	200	15	Plumbing fixtures, lock hardware, bushings, ornamental castings
Magnesium AZ91 B (9 Al-0.7 Zn)	230	160	3	Power tools, automotive parts, sporting goods
Zinc No. 3 (4 Al)	280	--	10	Automotive parts, office equipment, household utensils, building hardware, toys
5 (4 Al-1 Cu)	320	--	7	Appliances, automotive parts, building hardware, business equipment

Source: Data from American Die Casting Institute

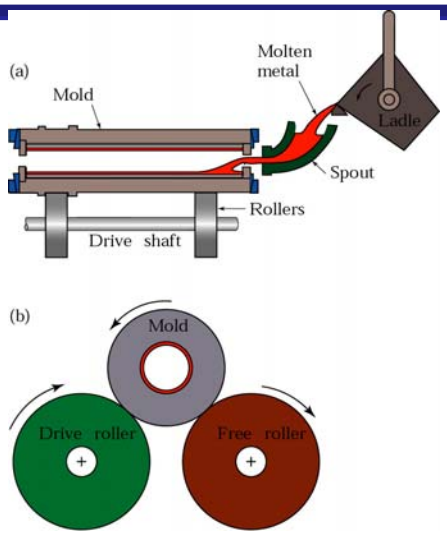
Die Casting Process



Example of Components that can be manufactured through Die Casting Process

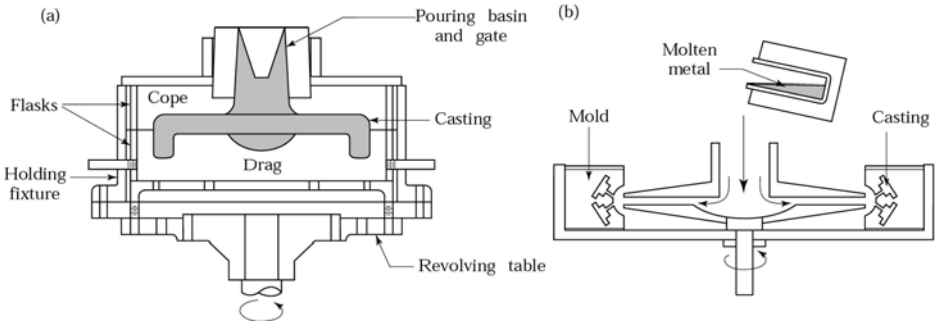
Harley's engine parts

Centrifugal Casting Process



Schematic illustration of the centrifugal casting process. Pipes, cylinder liners, and similarly shaped parts can be cast with this process.

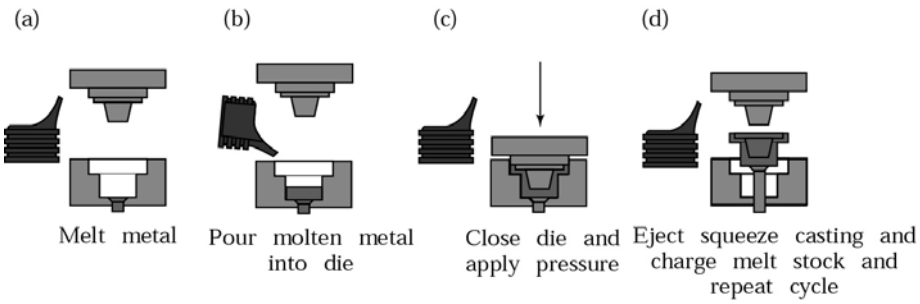
Semicentrifugal & Centrifuge Casting



(a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process.
(b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal force.

Squeeze-Casting

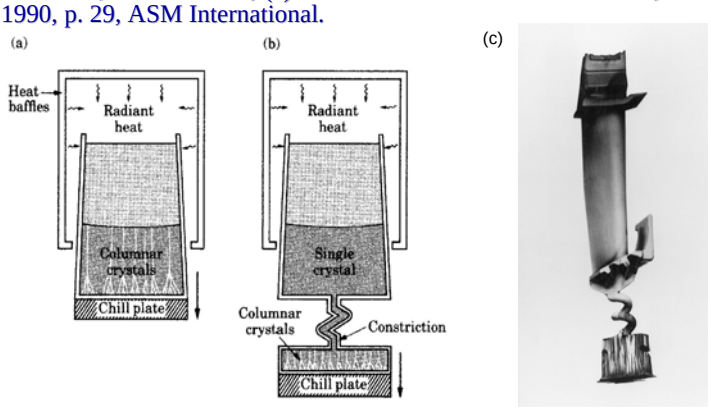
also called Liquid metal forging



Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging.

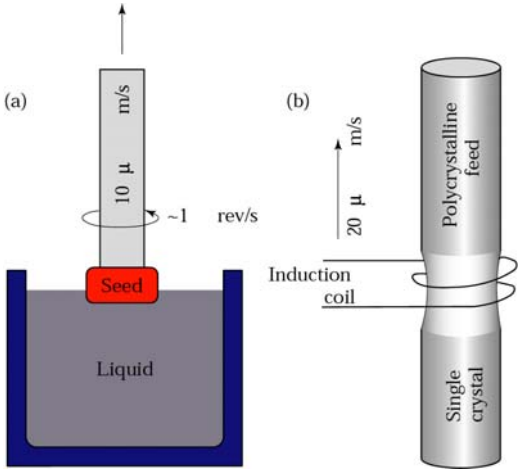
Single Crystal Casting of Turbine Blades

Methods of casting turbine blades: (a) directional solidification; (b) method to produce a single-crystal blade; and (c) a single-crystal blade with the constriction portion still attached. *Source*: (a) and (b) B. H. Kear, *Scientific American*, October 1986; (c) *Advanced Materials and Processes*, October 1990, p. 29, ASM International.

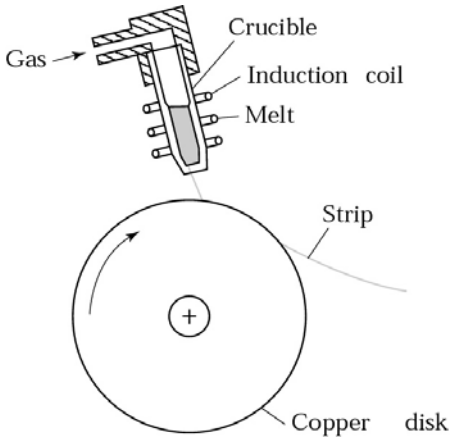


Single Crystal Casting

Two methods of crystal growing: (a) crystal pulling (Czochralski process) and (b) the floating-zone method. Crystal growing is especially important in the semiconductor industry. *Source*: L. H. Van Vlack, *Materials for Engineering*. Addison-Wesley Publishing Co., Inc., 1982.



Melt Spinning

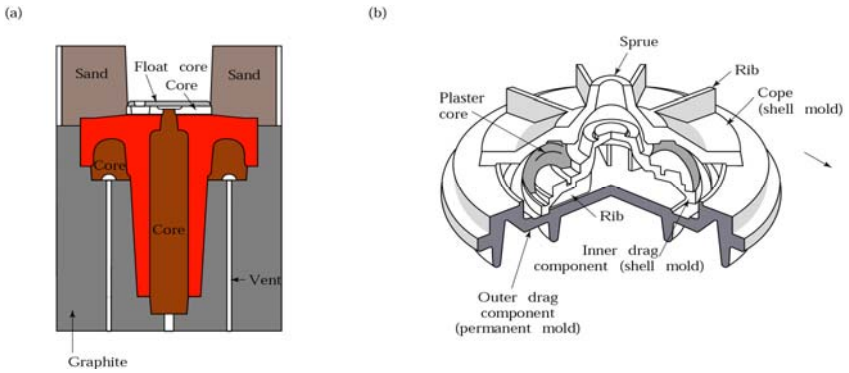


Schematic illustration of melt-spinning to produce thin strips of amorphous metal.

Trends in Casting Process

- Computer-aided design and manufacturing castings, molds and dies, gating and runner systems are being implemented at a rapid rate
- Automation of the process to reduce costs – use of controls, sensors, and robots
- R & D – automated inspection of castings using machine vision
- Improvements in melting and re-melting techniques, refinement of metal prior to pouring
- Investment castings continue to be an efficient metal-shaping technology for complex components (aerospace, high temperature applications
- Environmental impact of foundry process being studied

Composite Molds



(a) Schematic illustration of a semipermanent composite mold. *Source*: *Steel Castings Handbook*, 5th ed. Steel Founders' Society of America, 1980. (b) A composite mold used in casting an aluminum-alloy torque converter. This part was previously cast in an all-plaster mold. *Source*: *Metals Handbook*, vol. 5, 8th ed.

Comparison of Casting Process

SOME CASTING PROCESSES, THEIR ADVANTAGES AND LIMITATIONS

Die Casting	Excellent dimensional accuracy and surface finish; high production rate	Die cost is high; part size limited; usually limited to non ferrous metals; long lead time
Investment Casting	Intricate shapes;excellent surface finish and accuracy; almost any metal cast	Part size limited; expensive patterns, mold, and labor
Sand Casting	Almost any metal is cast; no limit to size, shape or weight; low tooling cost	Some finishing required; somewhat coarse finish; wide tolerances

Comparison of Casting Process

SOME CASTING PROCESSES, THEIR ADVANTAGES AND LIMITATIONS

Shell Mold Casting	Good dimensional accuracy and surface finish; high production rate	Part size limited; Expensive Patterns and equipment required
Permanent Mold Casting	Good surface finish & dimensional accuracy; high prodn. rate; low porosity	High mold cost; limited shape & intricacy; not suitable for high melting point metals
Expendable pattern	Almost any metal is cast; no limit to size; complex shapes;	Patterns have low strength; costly for small quantities

Casting Practices

- Casting practices are the techniques, methods and operations used in casting.
- It includes things like safety, fluxes, master alloys, furnaces,. All of which contribute to producing a quality part in a safe manner
- Safety is ***extremely*** important in a cast house because molten metal is very dangerous

Safety in Casting

- Concerns
  - Splashing of molten metal
  - Fumes from the molten metal
  - Dust from the sand
  - Fuels for the furnace, their control and proper operation of the equipment supplying them to the furnace
  - Water
    - Water and molten metal is extremely explosive since the high temperature of the melt rapidly converts it to steam
  - Handling of fluxes which can absorb water
  - Faulty equipment especially cracks in molten metal containers such as ladles

Fluxes and Slags

- Fluxes are inorganic compounds that
  - refine the molten metal by removing dissolved gases and impurities
  - perform other functions
    - Prevent oxidation (aluminum casting)
    - Cleaning
    - Wall cleaning
    - Slag forming
- Fluxes are mostly compounds of chorides, fluorides and borates of aluminum, calcium, magnesium potassium and sodium.
- Some fluxes form an insulating cover for the melt to prevent oxidation. They form Slags

Melting Furnaces

- Most common types are:
  - Electric Arc
    - have higher melting rate and lower pollution than most others
  - Induction
    - Coreless induction furnaces provide excellent mixing
    - Cored induction furnaces typically used for superheating and holding furnaces
  - Crucible
    - heated by oil, gas or electricity
    - may be stationary, tilting or moveable
  - Cupola
    - Large furnaces for making steel with layers of iron, coke and flux
    - Operate continuously

Design Guidelines for all Casting

- General Design Principles
  - Avoid sharp corners, angles and fillets
  - Avoid sharp section changes (blend smoothly)
  - Avoid large flat areas (use ribs and serrations)
  - Allow for shrinkage
  - Design parting line in appropriate location
  - Design in draft angles (for release of casting from mold)
  - Do not ask process to deliver higher tolerances than it can deliver
  - Allow extra material for finishing
  - Consider stress relieving
  - Enlist the help of a casting company

Kalpakjian Chapter 12

General Casting Economics

Process	Die	Cost Equip	Labor	Production Rate (Pc/hr)
Sand	L	L	L-M	<20
Shell-mold	L-M	M-H	L-M	<50
Plaster	L-M	M	M-H	<10
Investment	M-H	L-M	H	<1000
Permanent mold	M	M	L_M	<60
Die	H	H	L-M	<200
Centrifugal	M	H	L-M	<50

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