

Casting Processes



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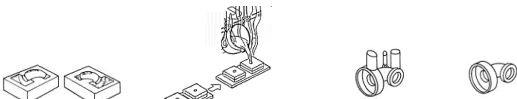
What are we going to cover in the next session;



- Sand
- Gravity Die & Pressure Die
- Centrifugal
- Shell Mould
- Investment
- Expendable Pattern
- Plaster Mould
- Ceramic Mould
- Permanent Mould

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Casting overview



Refractory mold → pour liquid metal → solidify, remove → finish

- **Versatile**
 - Complex geometry, internal cavities, hollow sections
 - Small (~10 grams) to very large parts (~1000 Kg)
- **Economical**
 - Little wastage (extra metal is re-used)
- **Isotropic**
 - Cast parts have same properties along all directions

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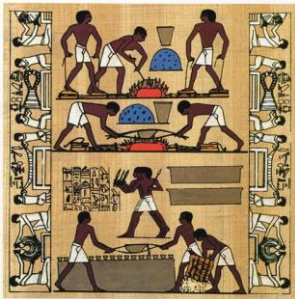
Historical timeline of casting



- 3200 BC - The oldest known casting in existence is cast in Mesopotamia.
- 2000 BC - Iron is discovered
- 800 BC to 700 BC - First Chinese production of cast iron.
- 645 BC - Earliest known Chinese sand moulding.
- 233 BC - Cast iron ploughshares are poured in China.
- 500 AD - Cast crucible steel is first produced in India, but the process is lost until 1750 when Benjamin Huntsman reinvents it in England.

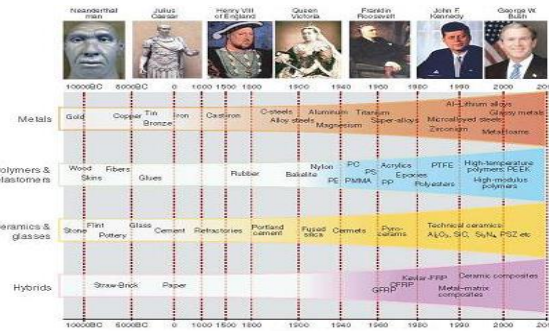
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Historical timeline of casting



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Historical timeline of casting



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Historical timeline of casting



Table 1 Chronological list of developments in the use of materials

Date	Development	Location
9000 B.C.	Earliest metal objects of wrought native copper	Near East
6500 B.C.	Earliest life-size statues, of plaster	Jordan
5000-3000 B.C.	Chalcolithic period; melting of copper; experimentation with smelting	Near East
3000-1500 B.C.	Bronze Age: arsenical copper and tin bronze alloys	Near East
3000-2500 B.C.	Lost wax casting of small objects	Near East
2500 B.C.	Granulation of gold and silver and their alloys	Near East
2400-2200 B.C.	Copper statue of Pharaoh Pepi I	Egypt
2000 B.C.	Bronze Age	Far East
1500 B.C.	Iron Age (wrought iron)	Near East
700-600 B.C.	Etruscan dust granulation	Italy
600 B.C.	Cast iron	China
224 B.C.	Colossus of Rhodes destroyed	Greece
200-300 A.D.	Use of mercury in gilding (amalgam gilding)	Roman world
1200-1450 A.D.	Introduction of cast iron (exact date and place unknown)	Europe
Circa 1122 A.D.	Theophilus's <i>On Divers Arts</i> , the first monograph on metalworking written by a craftsman	Germany
1252 A.D.	<i>Diabutsu</i> (Great Buddha) cast at Kamakura	Japan
Circa 1400 A.D.	Great Bell of Beijing cast	China
16th century	Sand introduced as mold material	France
1709	Cast iron produced with coke as fuel, Coalbrookdale	England
1715	Boring mill for cannon developed	Switzerland
1735	Great Bell of the Kremlin cast	Russia
1740	Cast steel developed by Benjamin Huntsman	England
1779	Cast iron used as architectural material, Ironbridge Gorge	England
1826	Zinc statuary	France
1838	Electrodeposition of copper	Russia, England
1884	Electrolytic refining of aluminum	United States, France

Applications



Engineering applications:

- 26% of castings produced in the UK.
- Includes energy production, mining, shipping, rail and pipes.



Aluminium nickel bronze propeller

Castings for wind turbines



Steel casing for a nuclear power plant (courtesy of Sheffield Forgemasters Engineering Ltd.)



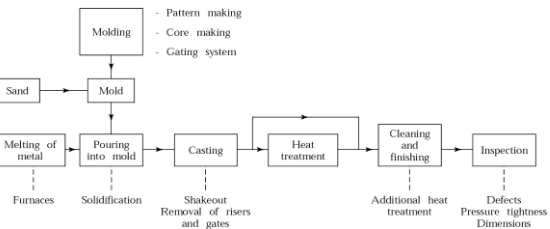
Cosworth Casting Process



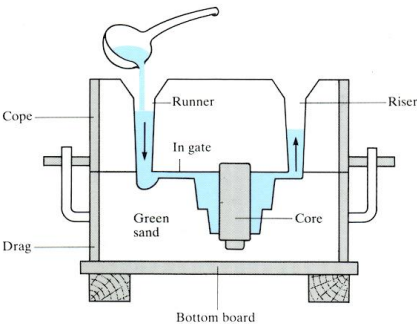
Cosworth Casting Process



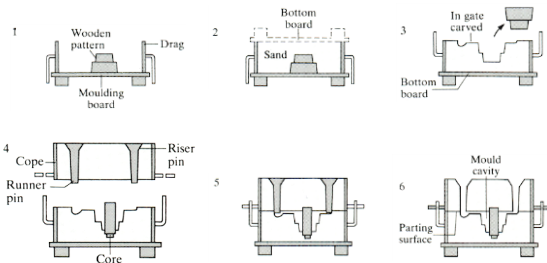
Sand Casting Process Steps



Sand Casting



Sand Casting



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Sand Casting



- Casting includes both 'ingot' and 'shape' casting.
 - 'ingot' casting is usually associated with the primary metal industry
 - 'shape' casting involves the production of more complex geometries.
- As one of the most versatile shaping processes as;
 - Includes complex geometries, external & internal shapes.
 - Possible to cast 'net shape' with no further machining operations.
 - Most are 'near net shape' where some additional machining is required.
 - Castings from a few grams up to 100 tons can be produced.
 - Using any metal that can be heated to a liquid state.
 - Suited to mass production techniques.

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Sand Casting



Potential Quality Issues

- Most casting process produce one of two failure defects;
 - Porosity
 - Inclusions (Unwanted second phase particles)
- In some applications, porosity can be tolerated. Why? Where?
- If we understand the process, the material properties, then we can develop and control our own processes.

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Sand Casting



- Limitations can include;
 - Mechanical properties
 - Porosity
 - Dimensional accuracy
 - Surface finish
- What do you think the important inputs and variables would be?
 - Solidification of the metal from its molten state (which usually is accompanied by shrinkage)
 - Flow of molten metal into the mould cavity
 - Heat transfer during solidification and cooling of the metal in the mould
 - Mould material and its influence on the casting process.

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Sand Casting



Considerations;

- How do we make the **pattern**?
 - Cut
 - Carve
 - Machine
 - Other 'new' technologies?
- Will the pattern be identical to the cast part required?
 - Shrinkage
 - Post-processing?
- What is the **parting line**?
 - How is this determined?



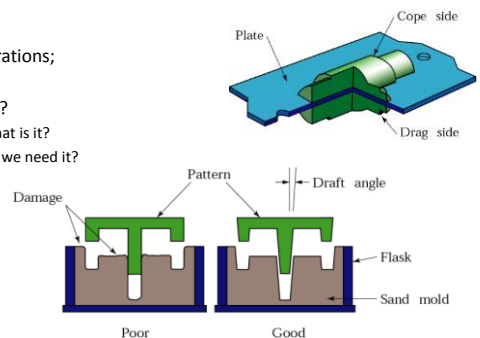
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Sand Casting



Considerations;

- Taper?
 - What is it?
 - Do we need it?



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Pattern Material



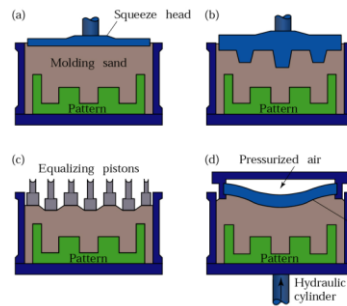
Characteristic	Rating ^a				
	Wood	Aluminum	Steel	Plastic	Cast iron
Machinability	E	G	F	G	G
Wear resistance	P	G	E	F	E
Strength	F	G	E	G	G
Weight	E	G	P	G	P
Repairability	E	P	G	F	G
Resistance to:					
Corrosion	E	E	P	E	P
Swelling	P	E	E	E	E

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.

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Sand compression



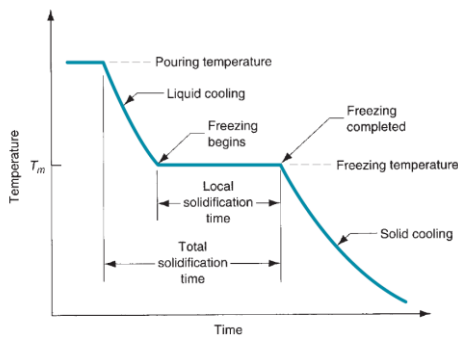
Various designs of squeeze heads for mold making;

- a) Conventional flat head
- b) Profile head
- c) Equalizing squeeze pistons
- d) Flexible diaphragm.

Source: © Institute of British Foundrymen.

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Solidification



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Chvorinov's Rule



- Total solidification time is the total time required for the casting to solidify after pouring.
- What is it dependent on?
 - Size
 - Shape
- The relationship between these is known as Chvorinov's Rule.

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Chvorinov's Rule



$$T_{TS} = C_m (V/A)^2$$

- T_{TS} = Total Solidification Time
- V = Volume of the casting (cm^3)
- A = Surface area of the casting (cm^2)
- C_m = Mould Constant (min/cm^2)

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Mould Constant



- Mould Constant depends on particular casting conditions;
- Mould material (specific heat, thermal conductivity)
- Thermal properties of the cast metal (heat of fusion, specific heat, thermal conductivity)
- Pouring temperature relative to the melting temperature.
- Can be based on experimental data from previous castings carried out using the same mould material and pouring temperature, even though the part may be of a different design.

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

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Task!



- In the casting of steel under certain mould conditions, the mould constant in Chvorinov's Rule is known to be 4.0 min/cm³ based on previous experience.
- The casting is a flat plate whose length is 28.5cm, width is 6.5cm, and thickness is 18mm.
- Determine how long it will take for the casting to solidify.

$$T_{TS} = C_m (V/A)^2$$

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Solution



- Volume $V = 28.5\text{cm} \times 6.5\text{cm} \times 1.8\text{mm} = 333.45\text{cm}^3$
- Area $A = 2((28.5 \times 6.5) + (28.5 \times 1.8) + (6.5 \times 1.8)) = 496.5\text{cm}^2$
- Chvorinov's rule: $T_{TS} = C_m (V/A)^2 = 4(333.45/496.5)^2 = 1.80\text{ min}$

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Casting Design



- Why is this important? What does Chvorinov's show?
- A casting with a higher volume-to-surface area ratio will cool and solidify more slowly than one with a lower ratio.
- This principle is put to good use in designing the riser in a mould. To perform its function of feeding molten metal to the main cavity, the metal in the riser must remain in liquid phase longer than the casting.

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Casting Design



- T_{TS} for the riser must exceed T_{TS} for the casting.
- How can we make this happen and by how much?
- Moulding conditions for the casting and riser are the same in terms of metal and mould conditions.
- Through design of the riser.

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Riser Design



- The casting is a flat plate whose length is 7.5cm, width is 12.5cm, and thickness is 2cm.
- The cylinder for the riser will have a diameter to height ratio of 1.0. Determine the dimensions of the riser so that its $T_{TS} = 2$ minutes
- Given that $T_{TS} = 1.6$ min, we can determine the mould constant C_m using a value of $n = 2$ in the equation;

$$\begin{aligned} C_m &= T_{TS}/(V/A)^2 \\ C_m &= 1.6 / (187.5 / 267.5)^2 \\ &= \underline{\underline{3.26 \text{ min} / \text{cm}^3}} \end{aligned}$$

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Riser Design



- So therefore we must design the riser so that its solidification time is 2 minutes. Using the same mould constant.
- The volume of the riser is given by;
 $V = \pi D^2 h / 4$
- And the Surface area given by;
 $A = \pi D h + 2\pi D^2 / 4$

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Riser Design



- Since we're using a Diameter to Height ratio of 1.0, substituting D for H in the volume and area formula's we get;
- $V = \pi D^3/4$
- $A = \pi D^2 + 2\pi D^2/4 = \underline{1.5\pi D^2}$

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Riser Design



- Thus, the V/A Ratio = $D/6$. Using this ratio in Chvorinov's equation, we have;

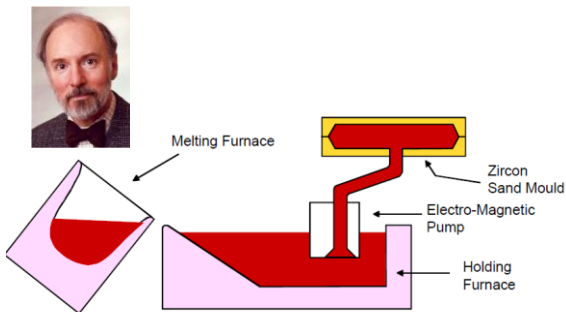
$$T_{TS} = 2.0 = 3.26 (D/6)^2 = 0.9056D^2$$

$$D^2 = 2.0/0.9056 = 22.086\text{cm}^2$$

$$D = 4.7\text{cm}$$

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Cosworth Process



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Cosworth Process



- Modern development for high volume production of high quality automotive castings.
- In this case, it is pumped uphill against gravity and this enables control to be maintained over the process of filling the mould.
- The large reservoir of liquid metal in the holding furnace allows time for impurities to sink or float.
- Electromagnetic pump (which contains no moving parts) displaces the best quality metal from the mid-depth of the holding furnace up and into the mould, displacing the air ahead of it as it goes.

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Cosworth Process



- The process is capable of a great degree of sophistication with the pump being programmable to fill each type of casting with an optimum filling program.
- In the latest variant of this process - the Mark II - the metal is introduced through the side wall of the mould which is then rolled over and detached from the filling system.
- This enables the throughput of moulds to be increased since it is no longer necessary to wait for the metal in one mould to solidify before the next mould is indexed into position at the pouring station.

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Cosworth Process



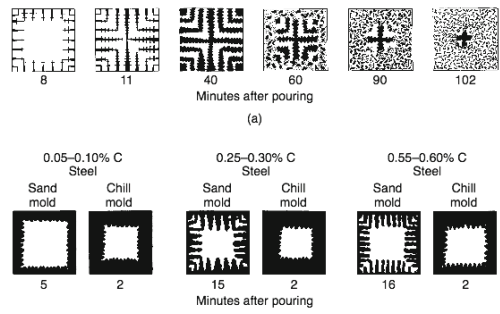
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Solidification Cracking (Porosity)



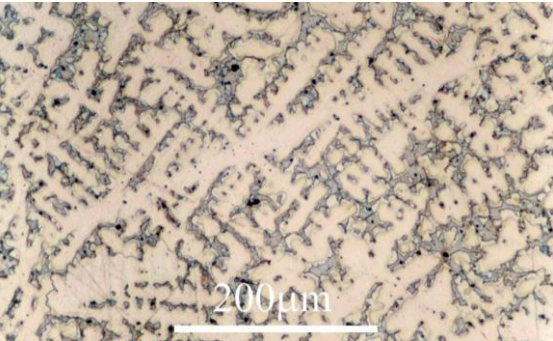
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Solidification Patterns



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Dendritic Casting Structure



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Core Sintering



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Surface Finish

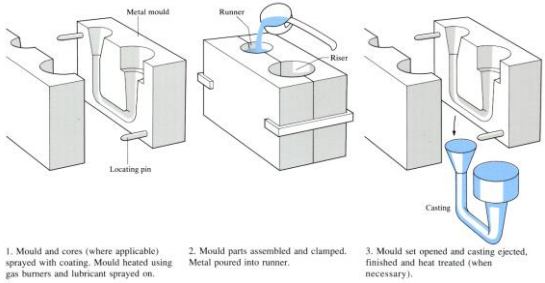


Surface roughness in casting and other metalworking processes.

Process	Roughness (R_a)														
	μ	m	50	25	12.5	6.3	3.2	1.6	0.80	0.40	0.20	0.10	0.05	0.025	0.012
Sand casting															
Hot rolling															
Permanent mold casting															
Investment casting															
Extruding															
Cold rolling, drawing															
Die casting															

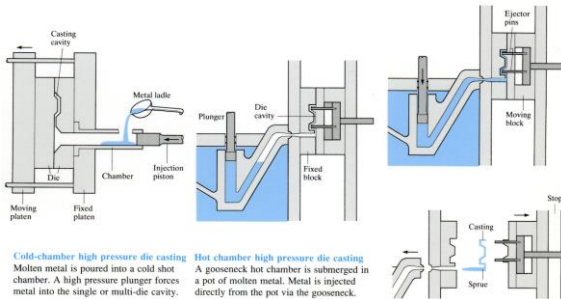
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Gravity Die Casting



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Pressure Die Casting



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Investment Casting



A pattern made of wax is coated with a refractory material to make mold, after which wax is melted away prior to pouring molten metal.

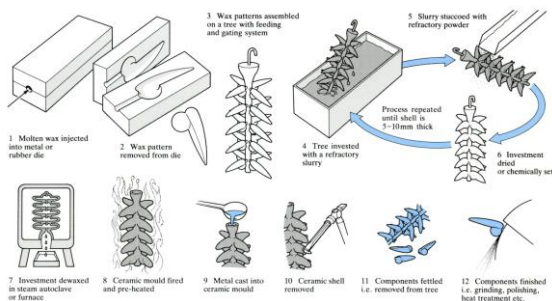


Picture: A one-piece compressor stator with 108 separate airfoils made by investment casting (photo courtesy of Howmet Corporation)

- 'Investment' comes from a less familiar definition of 'invest' - 'to cover completely' which refers to coating of refractory material around wax pattern
- It is a precision casting process - capable of producing castings of high accuracy and intricate detail

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Investment Casting



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Investment Casting



Advantages of investment casting:

- Parts of great complexity and intricacy can be cast
- Close dimensional control and good surface finish
- Wax can usually be recovered for reuse
- Additional machining is not normally required - this is a net shape process

Disadvantages

- Many processing steps are required
- Relatively expensive process

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Plaster Mould Casting



- Similar to sand casting except mould is made of plaster of Paris (gypsum - $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)
- In mould-making, plaster and water mixture is poured over plastic or metal pattern and allowed to set
- Wood patterns not generally used due to extended contact with water
- Plaster mixture readily flows around pattern, capturing its fine details and good surface finish

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Plaster Mould Casting



Advantages of plaster mould casting

- Good accuracy and surface finish
- Capability to make thin cross-sections

Disadvantages

- Mould must be baked to remove moisture, which can cause problems in casting
- Mould strength is lost if over-baked
- Plaster moulds cannot stand high temperatures, so limited to lower melting point alloys

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Manufacturing Technology



Ceramic Mould Casting

Similar to plaster mould casting except that mould is made of refractory ceramic material that can withstand higher temperatures than plaster

- Can be used to cast steels, cast irons, and other high-temperature alloys
- Applications similar to those of plaster mould casting except for the metals cast
- Advantages (good accuracy and finish) also similar

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Permanent Mould Casting Processes



- Economic disadvantage of expendable mold casting: a new mould is required for every casting
- In permanent mould casting, the mould is reused many times
- The processes include:
 - Basic permanent mould casting
 - Die casting
 - Centrifugal casting

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Permanent Mould Casting Processes



- Uses a metal mould constructed of two sections designed for easy, precise opening and closing
- Moulds used for casting lower melting point alloys are commonly made of steel or cast iron
- Moulds used for casting steel must be made of refractory material, due to the very high pouring temperatures

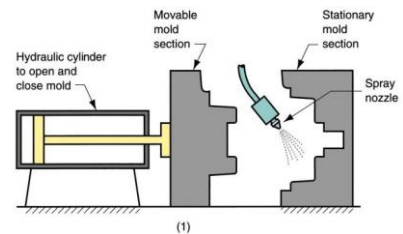
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Manufacturing Technology



Permanent Mould Casting Processes

- Steps in permanent mould casting: (1) mold is preheated and coated

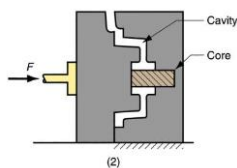


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Permanent Mould Casting Processes



- Steps in permanent mould casting: (2) cores (if used) are inserted and mould is closed

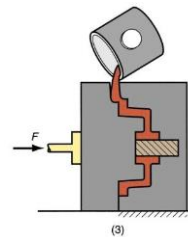


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Permanent Mould Casting Processes



- Steps in permanent mould casting: (3) molten metal is poured into the mould, where it solidifies.



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Permanent Mould Casting Processes



- Due to high mold cost, process is best suited to high volume production and can be automated accordingly
- Typical parts: automotive pistons, pump bodies, and certain castings for aircraft and missiles
- Metals commonly cast: aluminum, magnesium, copper-base alloys, cast iron
- Advantages of permanent mold casting:
 - Good dimensional control and surface finish
 - More rapid solidification caused by the cold metal mold results in a finer grain structure, so castings are stronger
- Limitations
 - Generally limited to metals of lower melting point
 - Simpler part geometries compared to sand casting because of need to open the mold
 - High cost of mold

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Casting Quality



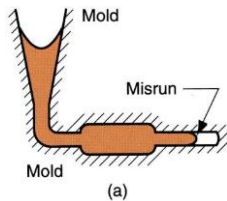
- There are numerous opportunities for things to go wrong in a casting operation, resulting in quality defects in the product
- The defects can be classified as follows:
 - General defects common to all casting processes
 - Defects related to sand casting process

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Casting Quality - Misrun



A casting that has solidified before completely filling mold cavity

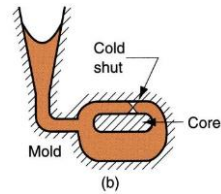


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Casting Quality – Cold Shut



Two portions of metal flow together but there is a lack of fusion due to premature freezing

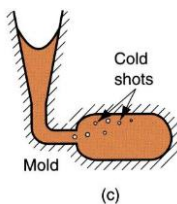


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Casting Quality – Cold Shot



Metal splatters during pouring and solid globules form and become entrapped in casting



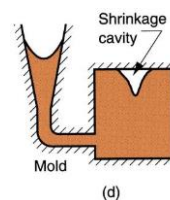
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Manufacturing Technology



Casting Quality – Shrinkage Cavity

Depression in surface or internal void caused by solidification shrinkage that restricts amount of molten metal available in last region to freeze

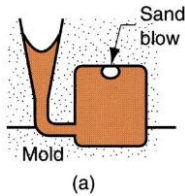


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Casting Quality – Sand Blow



Balloon-shaped gas cavity caused by release of mold gases during pouring

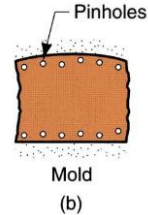


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Casting Quality – Pin Holes



Formation of many small gas cavities at or slightly below surface of casting

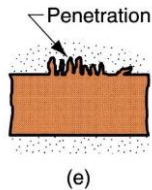


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Casting Quality – Penetration



When fluidity of liquid metal is high, it may penetrate into sand mold or core, causing casting surface to consist of a mixture of sand grains and metal.

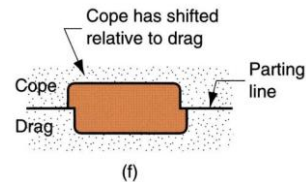


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Casting Quality – Mould Shift



A step in cast product at parting line caused by sidewise relative displacement of cope and drag.



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General Product Design Guidelines



- Holes
 - Holes are quite feasible in plastic moldings, but they complicate mold design and part removal
- Draft
 - A molded part should be designed with a draft on its sides to facilitate removal from mold
 - Especially important on inside wall of a cup-shaped part because plastic contracts against positive mold shape. Recommended draft:
 - For thermosets; $\sim 0.5^\circ$ to 1°
 - For thermoplastics; $\sim 0.125^\circ$ to 0.5°

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General Product Design Guidelines



- Tolerances
 - Although shrinkage is predictable under closely controlled conditions, generous tolerances are desirable for injection moldings because of
 - Variations in process parameters that affect shrinkage
 - Diversity of part geometries encountered
- Corner radii and fillets
 - Sharp corners, both external and internal, are undesirable in molded parts
 - They interrupt smooth flow of the melt, tend to create surface defects, and cause stress concentrations in the part

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