3. PROCESSES BASED ON SOLIDIFICATION

3.1. Preface

In this class of processes (often termed 'casting') the shaped solids are manufactured by introducing (eg pouring) a liquid into a cavity delimited by a mould, and permitting solidification. Most materials that have an accessible liquid state can be cast, and substances such as glass, clay and metallics have been cast since ancient times. Contemporary industrial processes include variety of techniques for casting metallics, polymers, glasses, ceramics, and a number of techniques for producing composites also involve casting operations. A large portion of casting operations figure on the boundary of primary and intermediate fabrication, and most solid products are at some point of their genesis treated by a casting technique.

The basic idea is that liquid readily fills an empty space delimited by solid walls. Gravitational force is readily employed, but centrifugal forces and other methods of increasing pressure are also applied. Once the liquid has assumed the desired form, a solidification process is promoted using various methods. Through experience over the centuries, the skills and techniques of casting have been conveyed and mastered.

A classical example of a (very) large product in existence is a cast bronze statue of the Great Sun Buddha in Japan over 15 m high (the Colossus of Rhodes bronze statue in Greece was over 30 m high before being overthrown by an earthquake some 2200 years ago). On the other side, technique termed 'microcasting' enables manufacture of metallic products such as electrical conductor windings with cross sections as small as 0.1x0.2 mm. Novel technique of 'freeze casting ceramic components' enables manufacture of products in sizes over 2 m within the tolerances of ±0.2 mm.

This wide variety of casting techniques is the result of attempts to optimize the process, i.e. to marry the requirements of quality of the product (e.g. mechanical properties) and process capability (e.g. castability in dimensions with given tolerances) with an overall economic rationale. The following examples present some of requirements common to all casting techniques:

- A cavity must provide (by means of a suitable mould) appropriate geometry allowing for filling (flow) and shrinkage after solidification. It must be possible to separate the solidified product from the mould. Furthermore, the mould must not cause too much restraint on the product shrinkage, otherwise excessive residual stresses and cracks may occur in the product.
- The mould material must not only have satisfactory mechanical and refractory properties, but should also provide appropriate heat and mass transfer and be chemically inert with regard to the liquefied charge.
- The cast material should have suitable physical and chemical attributes, e.g. liquidness and melting temperature, to permit the manufacture of a solid product of the required quality.
- The process parameters (eg pouring rate and temperature) should provide appropriate fluid flow; heat transfer conditions should allow for achieving both appropriate global geometry as well as satisfactory internal structure of the product. Solidification processes will significantly affect the attributes of the product, e.g. the inner structure.

The usual classifications of casting techniques are based on the type of cast materials (e.g. plastics, metallics, ceramics), on a specific technical aspect of the process (e.g. expendable and permanent mould), etc. Figure 3.1 presents one example of classifying the casting techniques.

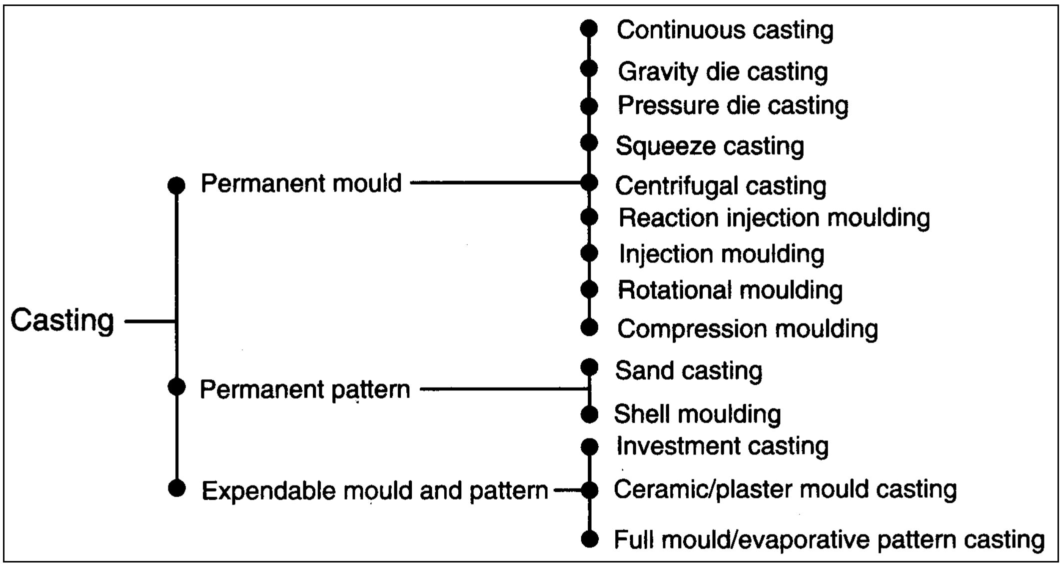
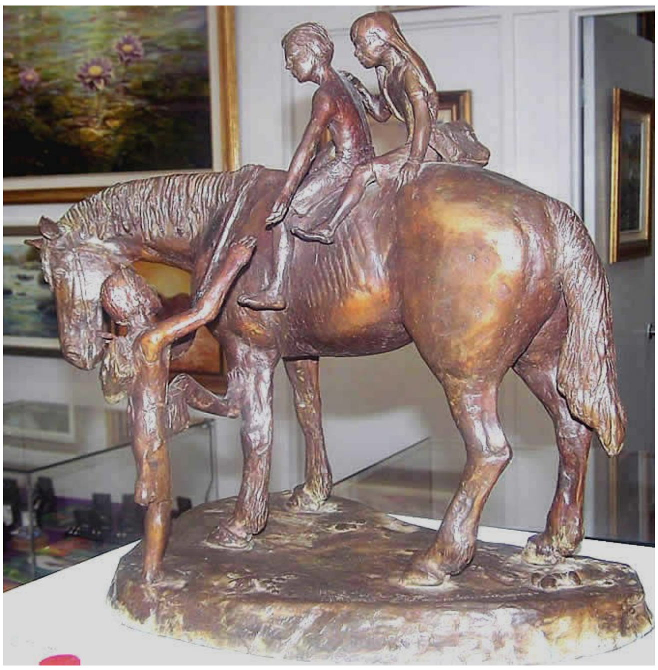


Fig 3.1: An example of classification of casting techniques

The casting process consists of more than simply pouring molten metallic material into a mould. There are many additional operations needed prior to and after the pour, for example: pattern preparation, core making, cleaning and surface finishing of the casting. Each casting technique has advantages and limitations. The engineer must first decide whether casting should be selected in the first place – other manufacturing process may be more suitable. If casting is chosen, the appropriate casting technique should be selected and optimum process parameters should be proposed for each specific product.

In this publication, an educative introduction to typical casting methods is made, following the criteria of their illustrativeness and contemporary significance.



Australian artist Wayne Strickland uses the 'lost wax' method of casting bronze, a technique which is both difficult and labour intensive, but allows for the precision and fine detail.

3.2. Examples of Manufacturing Processes

3.2.1. Casting in Sand, Plaster and Ceramic Moulds

- ♦ Sand casting
- ♦ Evaporative-pattern casting
- ♦ Plaster mould casting
- ♦ Ceramic mould casting

♦ Sand casting

Sand casting represents historically one of the early stages in the development of the casting methods, and it is still the most widely used technique.

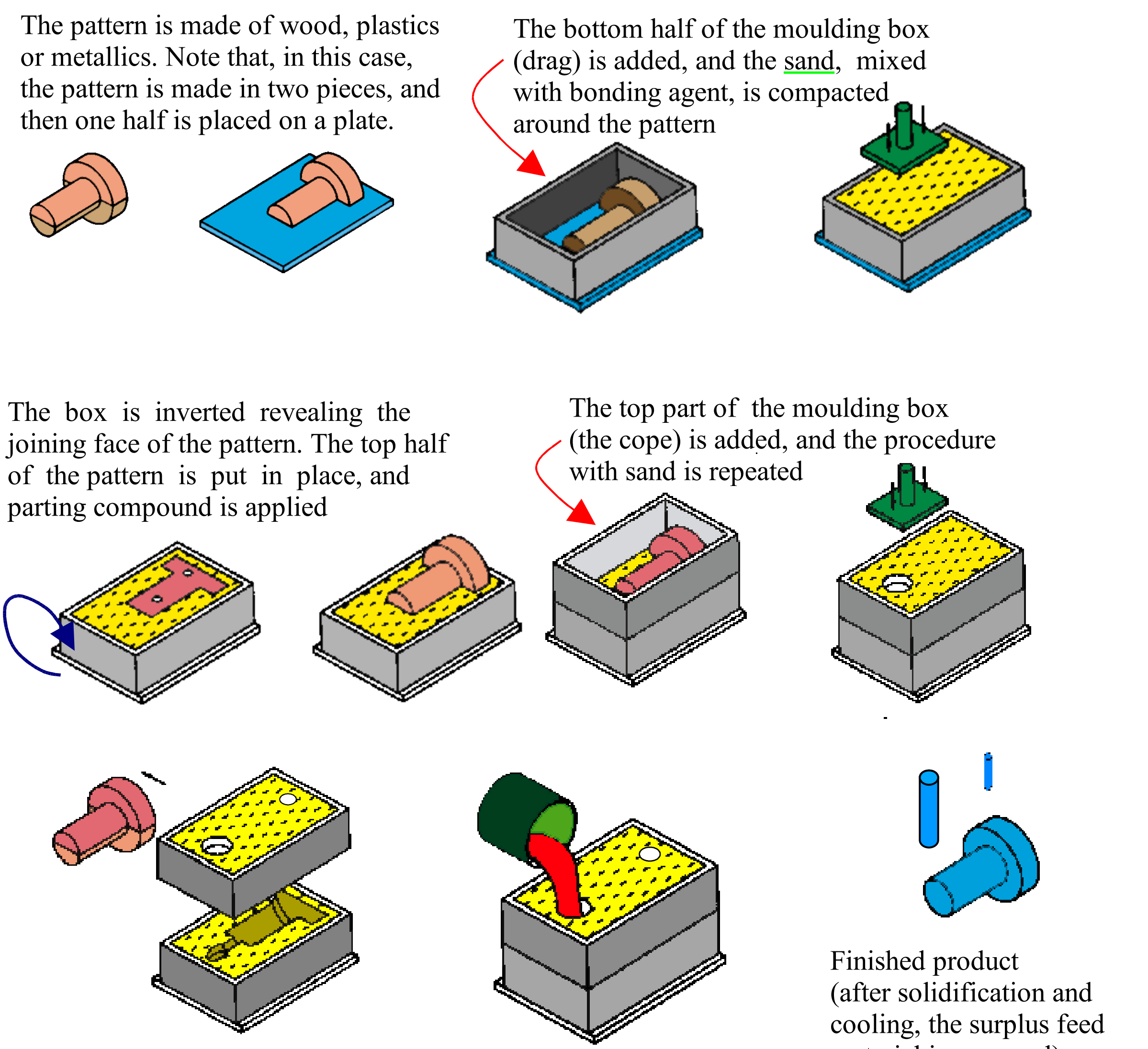


Fig 3.2: Typical sand casting process [326, 329, 525, 575]

This technique embodies solutions to the problem of how to create a vessel (cavity) within which a liquid of initial temperature above 500 or 1000 °C will solidify into a desired and often complex shape. As a first step, the mould is made out of an impressionable matrix mixed with bonding substances. Sand is one of the original materials and is still used for this purpose. This matrix is pressed around a pattern of the object to be cast and by this impression the product-shaped cavity is created. This cavity is subsequently filled with the casting liquid, which solidifies into the shape of the product Fig 3.2.

Openings in the mould, called the pouring basin, sprue, choke, gates, runners, and risers, are added to allow for appropriate motion of the fluid and for heat transfer Fig 3.3.

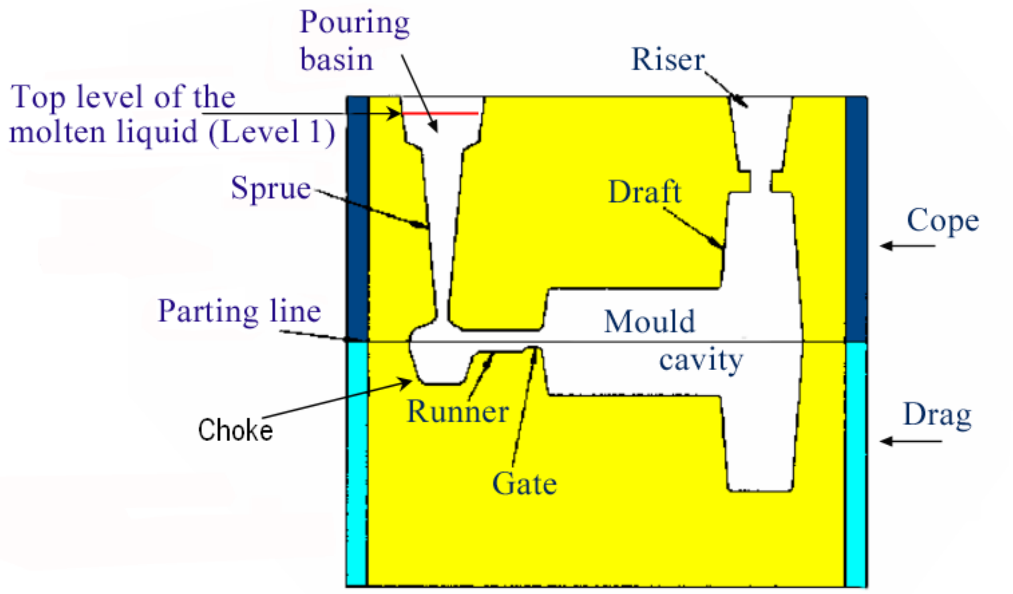


Fig 3.3: Sand mould for the casting process shown in Fig 3.2. [326, 329, 575]

The pouring basin receives the melt before it flows down the gating system (it has an increased diameter to stabilize turbulence and variations in the level of poured liquid; sometimes it contains a filter to hold back inclusions). Hydrostatic pressure at the top surface of the liquid (Level 1 in Fig 3.3) is at a minimum (equal to atmospheric pressure), while the potential energy of the liquid at this point has a maximum value.

The choke and gate are designed to dissipate the kinetic energy that the liquid has gained by the time it reaches the bottom of the sprue. The choke bottom may be made of a ceramic material (splash core) to prevent erosion. The gate has a narrowed cross-section to compensate for sudden change in flow direction and to ensure laminar flow. Runners connect the sprue with the risers and mould cavity.

The open riser provides a reservoir for the molten metal, it allows for the escape of gases as the molten metallic is poured into the mould and finally, it keeps the shrinkage cavity out of the product shape. Blind risers are often made to provide reservoirs for molten metallic material and heat energy, and also to allow for the escape of certain gases, as well as to entrap slag and inclusions.

The whole gating system and mould cavity should be designed to minimize turbulence at any point. For example, any sharp corners should be avoided even if that causes a need for subsequent removal of thicker allowance layers from the solidified product.

When the sand is compacted sufficiently, the two parts (cope and drag) are separated and the pattern is removed. The pattern (needed to create the mould) is a replica of the product, yet with some important differences:

- It includes the geometrical allowances for shrinkage and for machining.
- It may be in one or more pieces; it may also incorporate a separate core so that a hollow product can be cast.

Patterns are usually made of wood, polymers or metallics. Their strength and durability affects the number of moulds that may be produced. Sand moulds are, as a rule, **expendable**, i.e. they serve for one cast product only (the sand is recycled after filtering and reconditioning). However, the same pattern can be used to produce a number of sand moulds.

♦ Evaporative-pattern casting

A special case of expendable pattern is that made of polystyrene, which evaporates upon contact with the molten metallics. The cavity for the casting is formed in situ, during the pouring. This process is termed **lost-pattern** or **evaporative-pattern casting** (also called Lost Foam as well as **Full-Mould process**). First, raw expandable polystyrene beads are placed in a preheated aluminum die. The polystyrene expands, fills the shape of the die cavity and after additional heating, fuses and bonds into the form of the pattern. Such a pattern is coated with refractory slurry and placed in a flask (the flask is made by permanently joining the cope and the drag into a compact container – the parting line is therefore eliminated). Several patterns may be joined in a complex assembly using hot-melt adhesives. The flask is then filled with sand to support the pattern. Finally, without removing the polystyrene pattern, the hot liquid is poured into the mould. The heat degrades the polystyrene and the pattern virtually evaporates and escapes into surrounding sand and through the open risers and vents.

A laminar flow of the melt can be achieved with Reynolds numbers Re = 400 ÷ 3000. Flow velocity depends on the rate of depolymerization at the melt-polymer front, and is estimated to be in the range 0.1 – 1 m/s. Producing patterns with internal hollow zones can control this velocity; thus the velocity decreases as the liquid fills these empty regions. Significant thermal gradients appear at the melt-polymer interface because the heat energy is consumed for depolymerization and evaporation.

Evaporative-pattern casting is relatively simple since no pattern removal is required. It is suitable for very complex shapes. Polystyrene is inexpensive and can be easy processed in a wide range of sizes with fine surface details. A major cost factor is the die for expanding the polystyrene beads into patterns. The casting process can be automated and the cast product requires minimum finishing and cleaning operations. Typical products of evaporative-pattern casting are crankshafts, brake elements, aluminum engine blocks and cylinder heads. Large and complex products can be cast conveniently using this method.

Recently, polymethylmethacrylate and polyalkylene carbonate have been used as pattern materials for ferrous castings. Further experiments have been made including the grain refiners and alloy modifiers, within evaporative patterns. An interesting application is a polymer pattern embedded throughout with fibers that, after pouring and solidification, become the integral part of the metal-matrix composite.

Knowledge of the detailed methods of mould preparation, and precise technical characteristics of the sands used in sand casting, developed over many centuries. Amongst the various types of sands used, the most common is green sand, which is generally a mixture of ordinary silica sand (SiO_2), clay, water, and other binding materials. Other binder agents/methods may be used, e.g.

(in)organic, synthetic etc. Metal-containing sands based on zircon may be used for certain types of casting. Basically the requirements on sand moulds include:

- Refractoriness (to withstand high temperatures)
- Cohesiveness (to retain geometry when compounded and packed in a mould)
- Permeability (to permit gas escape)
- Collapsibility (to permit the material to shrink).

In summary, various types of sand casting are widely applied in ~ 90% of contemporary manufacturing processes based on casting and solidification. The main advantages include no limit to product mass, and a feasibility of this technology for almost all metallics. The main limitations include **expendable mould**, relatively high surface roughness, and incapability to achieve tight geometric tolerances. Furthermore, high human involvement is required to produce acceptable quality (e.g. intricate details and satisfactory surface of the mould cavity).

♦ Plaster mould casting

Plaster mould casting can be considered to be special development of sand casting, where the mould is made of a gypsum slurry material. A precision metallic pattern is used during the first stage of forming the mould. Once the mould cavity has gained the initial form, the mould is separated from the pattern and baked in an oven, to remove the moisture. The composition of plaster slurry varies. Additives and fibres are sometimes used to control the mould expansion and strength. A plaster mould has low gas permeability, and gases may create porosity problems. Patterns can be made from metallics (usually brass), plaster, wood or thermosetting plastic. After pouring and solidification, the mould is broken to remove the product.

This process is limited to low melting temperature metallics i.e. Al, Cu, Zn, Mg, Pb and Sn alloys, since a plaster mould would degrade at elevated temperatures. Typical applications are pump impellers, waveguide components (for microwave applications), lock components, gears, valve parts, moulds for plastic and rubber processing (e.g. tyre moulds). The minimum section of product walls ranges from 0.8 to 1.8 mm. Products normally range from 25 to 50 kg (1000 kg products can also be made). Moderate to high complexity (sharp corners) are possible, including inserts, bosses and undercuts with little added cost. Surface details are good (0.8 – 3 µm Ra can be achieved). Little or no distortion is observed even on thin sections.

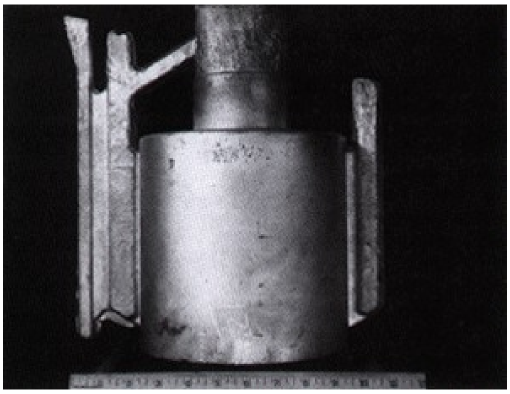


Fig 3.3a: Typical ZA-12 (zinc alloy) casting made from a plaster mould [436]

Normal production rates reach up to 10 pieces per hour. There are low scrap loses (waste is recycled). The design can easily be modified during production. Tooling and equipment costs are low to moderate. Finishing costs are low: little material removal is required except grinding for gate removal. Direct labour costs are high (some skilled operations are necessary).

♦ Ceramic mould casting

Ceramic mould can be considered to be another variation in the development from sand casting. A precision metallic pattern is often used to produce the **expendable** mould, which is made of ceramic slurry. Wide variations in composition of the ceramic slurry and curing mechanisms are employed. For example, the slurry can be made as a mixture of fine-grained zircon, ($ZrSiO_4$), aluminum oxide, and fused silica, which are mixed with bonding agents and poured over the pattern placed in a flask. The mould is then dried and baked.

After pouring and solidification, the mould is destroyed to remove the product. Ceramic moulds can be used for casting practically any contemporary metallic alloy, including high-temperature alloys. Typical products are all types of dies and moulds for other casting and forming processes (e.g. cutting tool bodies), components for food handling machines, pump impellers, aerospace and atomic reactor components. Very high complexity (combined with use of cores) is achievable. Inserts, bosses and undercuts are possible at little extra cost. The minimum section ranges from 0.6 mm to 1.2 mm, and the mass of products range from 100 g to 3000 kg. Products have low porosity and good mechanical properties, with good surface details (0.6 – 6.3 mm Ra can be achieved).

3.2.2. Ingot Casting and Continuous Casting

- ♦ **Introduction**
- ♦ **Ingot casting**
- ♦ **Continuous casting**

♦ Introduction

Casting the feed (ingots, blooms, slabs and billets) for further processing, generally involves producing a large quantity of simple shapes, mainly rectangular prisms. Feed production in the steel industry is mainly performed by means of continuous casting. Less frequently, other geometries e.g. circular cylindrical shapes are produced. Recently, continuous casting of so-called pre-shaped feed geometries for particular manufacturing processes (e.g. for rail production) has been introduced; however, such cases present only a small fraction of the total production of the cast feed.

Feed casting is a closing stage for primary refining operations, where the ore and additives are molten, metallics are purified and alloys are composed by means of physical and chemical reactions.

♦ Ingot casting

Traditional, and still broadly used initial step in processing metallics is casting the ingot Fig 3.3. This operation was introduced to prepare feed stock for later processing, e.g. forging and rolling processes. The important phenomena of microstructure formation during solidification are most obvious in casting ingots, due to the simple geometry of ingot moulds and the relatively steady state of liquid metallics.

The mass of ingots varies from several kilograms to over 100 tons. During ingot manufacture, a relatively high quantity of thermal energy (order of magnitude of 10^5 to 10^{10} J) should be supplied to the material to melt it in the first place. Once the liquid has assumed the shape of a cavity, the heat should be removed from the ingot-mould system.

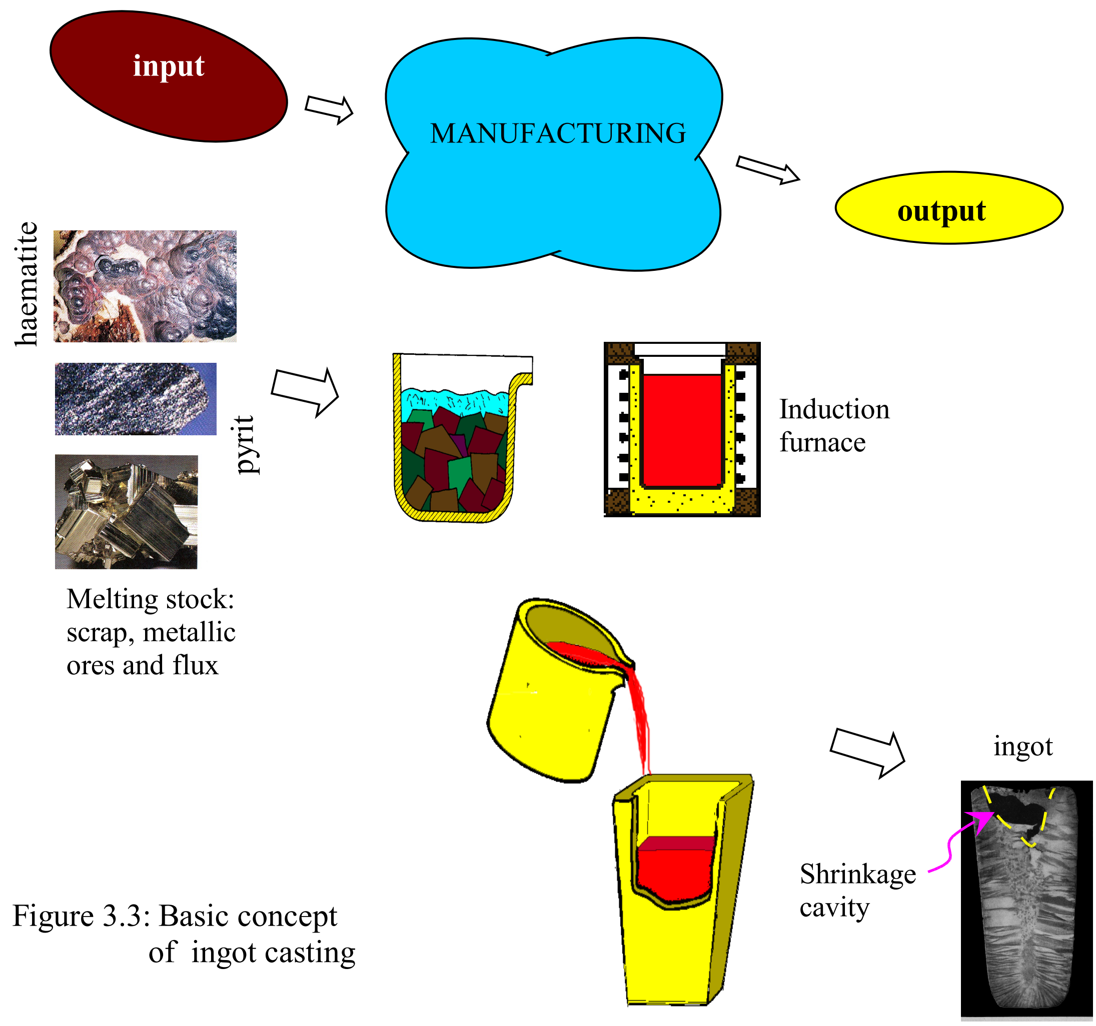


Figure 3.3: Basic concept of ingot casting

The geometry and the distribution of microstructure grains, the features dependent on the heat and material transfer during solidification, strongly affect the attributes of the solidified alloy, Fig 3.4.

At the surface of the ingot (along the interface mould – cast) a relatively thin band of randomly oriented equiaxed grains forms (zone "a"). Subsequently, towards the center of the ingot, elongated grains form a much thicker columnar zone"b". Finally, the equiaxed zone "c" of randomly oriented grains might be observed in the central part. One of the factors affecting the width "w" of this central zone is the fraction of alloying element: in the case of pure metal w = 0, i.e. the columnar zone continues to grow until all of the liquid has solidified.

Grains within the columnar zone exhibit dendritic growth Fig 3.4. Dendrites have branches and they grow from the cooler region (surface) towards the hotter central part; they also interlock with neighboring entities, which results in columnar dendrites. Note that liquid is entrapped between the dendrite branches, and also that inclusions are driven towards the solidifying front. All this contributes to microstructure segregation.

More detailed chemophysical aspects of the solidification will be presented in Section 3.3. At this point it is educative to note that such a heterogeneity in microstructure has a number of disadvantages:

- Strength, hardness and ductility of the cast material decrease as the grain size increases
- The probability of microporosity (interdendritic shrinkage voids) increases with grain size
- Adverse micro and macrosegregation adverse effects increase with grain size diversity.

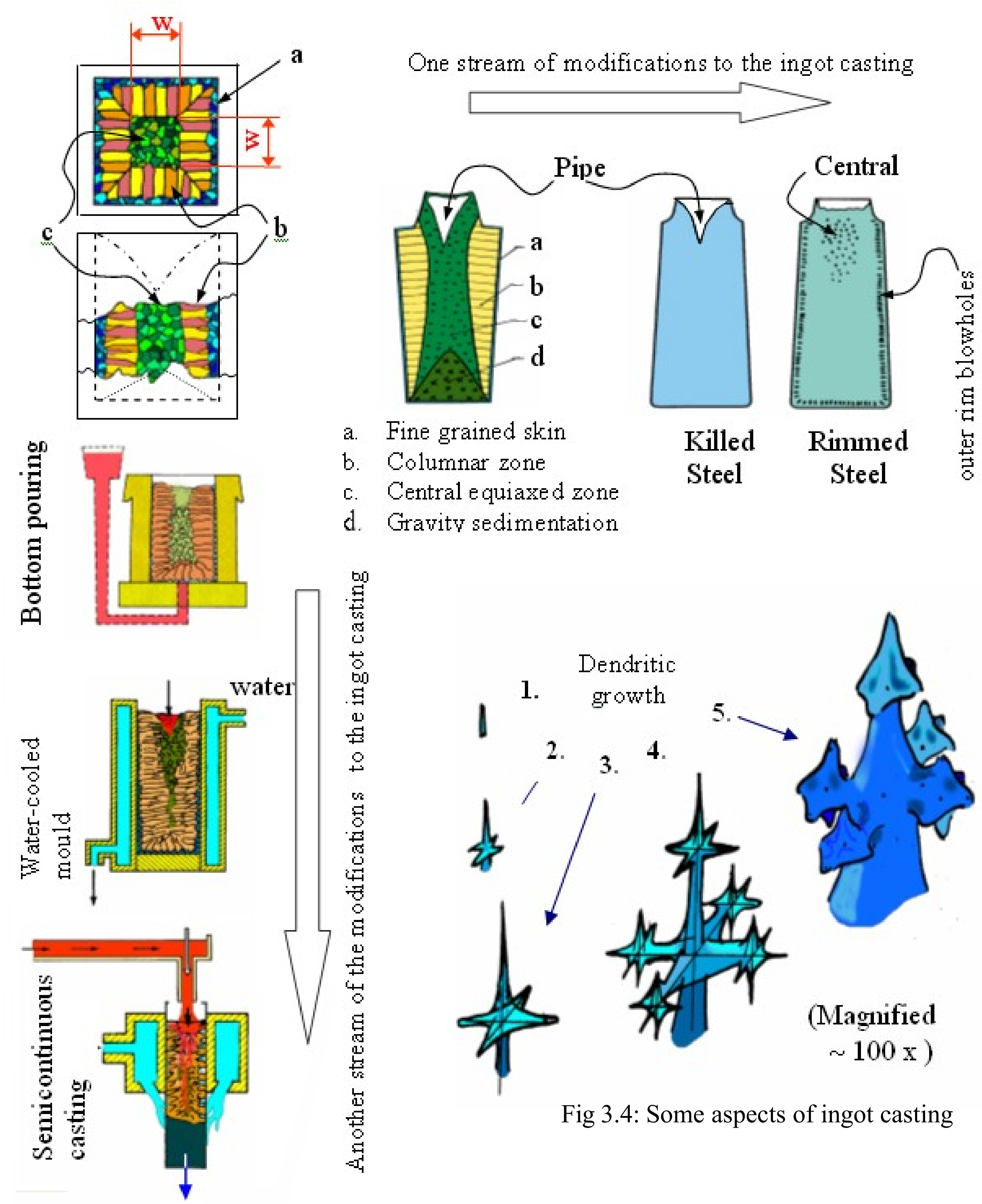


Fig 3.4: Some aspects of ingot casting

Ingots produced with a large and distinct columnar zone are prone to a range of defects e.g.:

- Anisotropy of properties due to the large grain zone causes improper material flow during rolling or forging – unexpected overfilling or underfilling in dies
- Porosity can open out at the surface and oxidation will create critical points that contribute to adverse effects in the final product (surface crack formation, corrosion spots, etc)
- Structural heterogeneity (micro and macro segregation) cause stress concentrations and increase the probability of fatigue failures.

Further typical drawbacks in casting individual ingots are formation of shrinkage cavity (pipe) and gravity sedimentation, Fig 3.4. Details of those phenomena, basically associated with heat transport, structural phase transformations and density variations, will be discussed in Section 3.3. If either problem occurs it is necessary to cut off the top/bottom section.

Difficulties involving individual mould preparation, ingot stripping and manipulation operations, present significant manufacturing issues.

To overcome the above hindrances, two main streams of improvement were developed based on theoretical and empirical analyses as well as laboratory and industrial experiments:

i) The global geometry of the ingot mould was adjusted, introducing for example side wall inclinations and a "hot top" attachment. The favorable geometry of the mould governed the heat transport phenomena suppressing the depth and volume of the pipe. Complementary healing techniques include:
- Control of degasification during the cooling of the liquid,
- Introduction the inner circulation of the liquid containing the solid phase e.g. by means of induction magnetic fields,
- Introduction of innoculants (nucleating agents) to increase the equiaxed zone.

ii) A second stream of improvement was introduced by changing the casting configuration as a whole, e.g. by introducing bottom pouring and gradually shifting from a static to a dynamic system:
- Bottom pouring Fig 3.4.
- Controlled heat transport via internally cooled mould walls,
- Semicontinuous casting

Various stages of ingot casting are applied corresponding to the attributes of the product, e.g.:
1) Precious metallics (e.g. gold, silver) are mainly cast using traditional ingots.
2) Feed for special products (e.g. large crank shafts, rolling mill rolls) is manufactured using highly improved techniques of individual ingot casting.
3) Vacuum remelting is an advanced technique for manufacturing extremely gas-free and clean metallic ingots. In electroslag remelting the ingot is treated as an electrode, melted and recast by means of an electric arc, with the surface covered by a thick blanket of molten flux.

♦ Continuous casting

Large-scale production of feed (mainly for rolling mills) is overwhelmingly characterized by the use of continuous casting blooms, slabs and billets, Fig 3.5, instead of batch casting of ingots.

Continuous casting of steels, Al and Cu alloys, combines the minimization of the columnar zone by controlled heat transfer (via a water cooled mould) which eliminates both the gravity sedimentation and shrinkage cavity (due to the speed and continuity of casting), Fig 3.5. All the above effects suppress the microstructure segregation, and in addition, the global geometry of the product is brought more closely to the required feed size, thus eliminating the whole segment of so called break-down mill operations. Continuous casting requires much tighter control of process parameters, and much higher capital investment in equipment. This process is justified for high quantities of products (order of magnitude 10^6 tonnes per year) which include slabs, blooms and billets (i.e. rectangular profiles with cross-sectional dimensions ranging from ~2 m to ~0.01 m). A mould wash prevents adhesion and welding of the melt to the mould. In steel casting, mould vibrations provide further prevention; in Al casting the molten zone can be contained with air pressure or with an electromagnetic field.

Ideally, the hot continuously cast product can enter the rolling mill directly, thus preserving the heat energy, rather than interrupting the material flow line, Fig 3.5a. In practice, the coordination of the simultaneous casting and rolling is often not feasible, and continuously cast feed sizes are cut to the required lengths, cooled down, inspected and stored. Less frequently the profiled shapes (feed) are continuously cast in an attempt to bypass further initial stages of rolling.

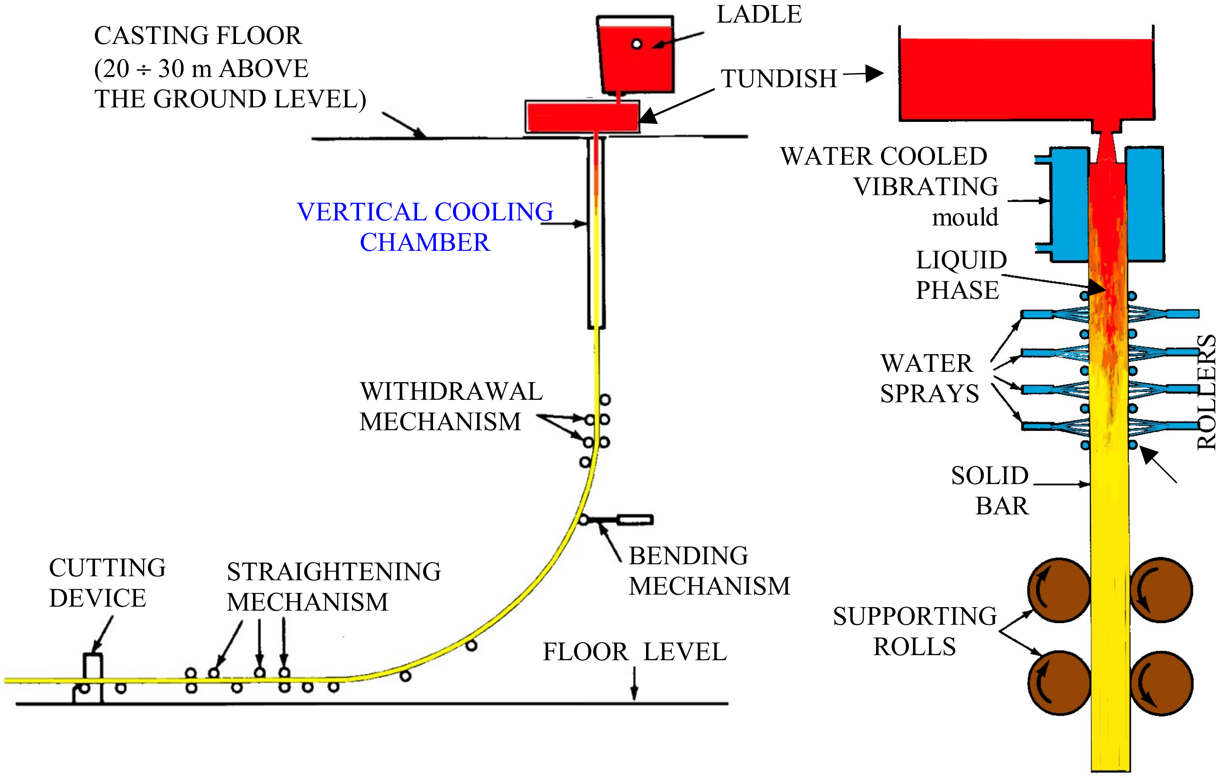


Fig 3.5: Continuous casting of steel blooms, slabs and billets [45]

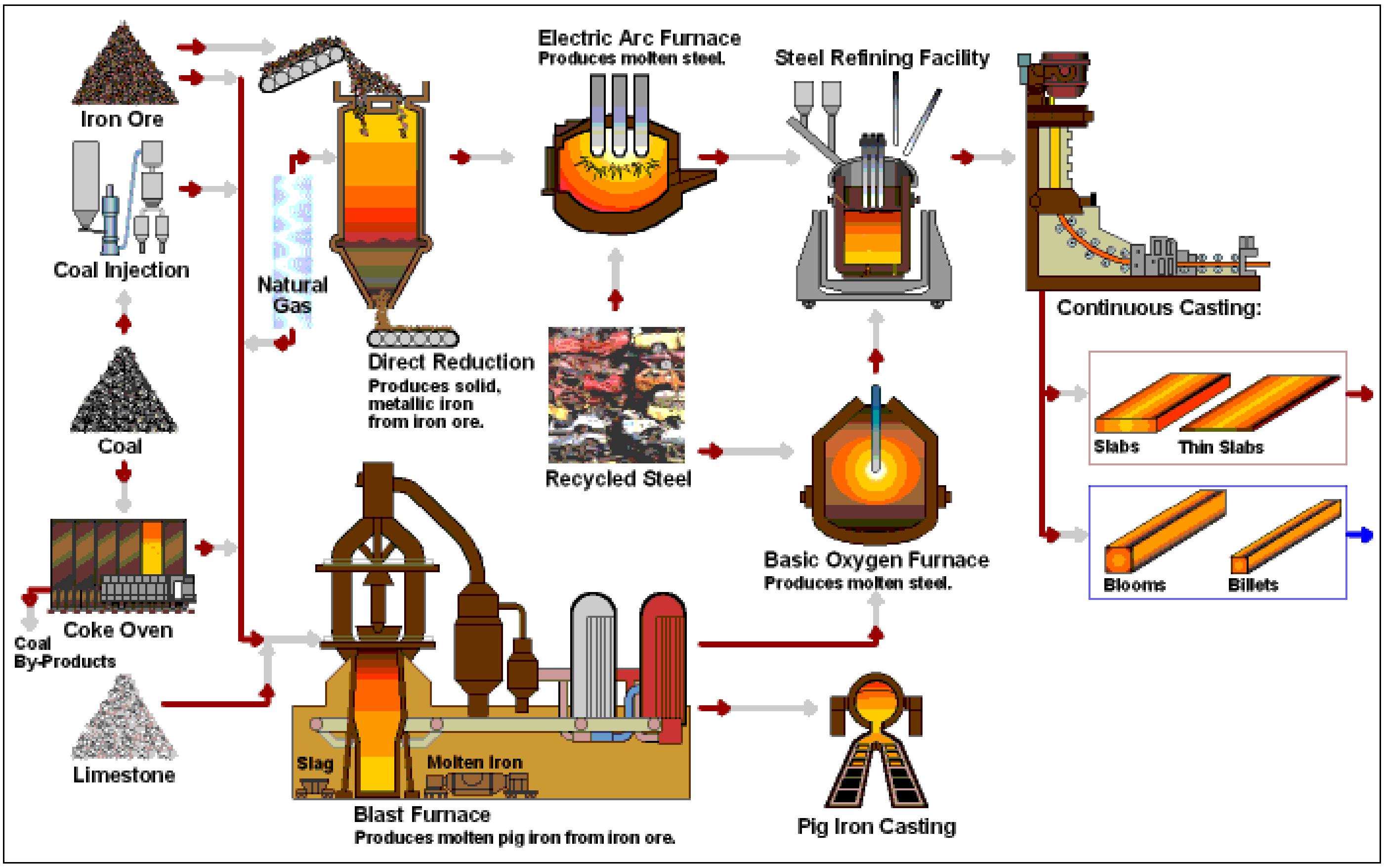


Fig 3.5a: Steelmaking flowlines [270]

Other types of continuous cast products include various long products with special cross sections, e.g. solid tubing and gears. A high quality product can be obtained by protecting the liquid from contamination during pouring and solidification.

3.2.3. Investment Casting and Shell-Mould Casting

- ♦ **Investment casting**
- ♦ **Shell-mould casting**

♦ Investment casting

Although Investment Casting (lost-wax process) has been known for over three millennia, this technique is still widely used for manufacturing (smaller size) products of intricate geometry to tight tolerances and smooth surface (tolerances are tighter than in either shell-mould — described below — or sand casting techniques) Fig 3.6.

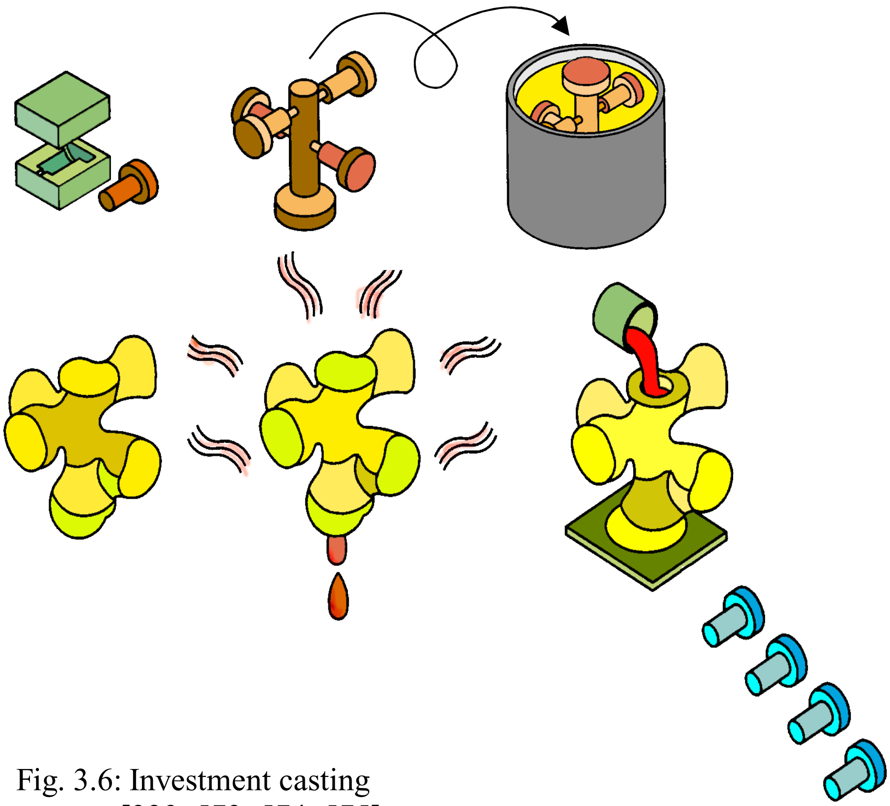


Fig. 3.6: Investment casting process [329, 573, 574, 575]

Wax patterns are cast (usually under pressure) in a permanent metallic die. A number (as many as possible) of patterns are attached to the sprue by soldering. Further stages can be highly automated: the pattern cluster passes through a series of dips of fused silica or ceramic slurry to provide appropriate coating layers. Fine colloidal silica wash is often dusted with refractory sand. Between dipping, the coatings partially dry in the air. The cluster is placed in a flask and the refractory material is poured around it. Next, the assembly is baked both to harden the refractory shell and to melt out the wax. Finally, the pouring of the actual cast fluid is performed usually in the hot mould, and after solidification, the investment mould is broken away from the casting.

In this method, both pattern and mould are expendable. The high investment in tooling in this particular technology is justified by the savings in subsequent machining. There is no parting line present, and the complexity of the geometry (including extremely thin casting – 0.4 mm) reaches the highest levels known in manufacturing by casting and solidification at atmospheric pressure.

Variations on the investment casting include diverse materials for producing the pattern (wax, frozen mercury, plastics), for creating the first coating layer (ceramic or silica shell), for production of secondary layers and finally, the modifications of the pouring operations (that can be conducted immediately after baking the mould to use the accumulated heat to avoid the adverse effects of humidity – this can also be achieved by pouring in a vacuum or argon).

Materials for investment cast products include almost all castable metallics, e.g. alloys of Ag, Au, Al, Cu, Ni and Co (superalloys), Fe (high temperature resistant steels). Products range in mass from 0.5 to 40 kg, and include jewelry, dental inlays, mechanical components (turbine blades, gears, cams, valves) and glass products.

♦ Shell-mould casting

Shell-mould casting was originally developed for plastics casting. A pattern is made usually of steel, which is dipped into molten lead, until a thin shell of lead is formed over the model. The steel pattern is then pulled out of the lead shell, leaving a thin lead mould – a shell. Liquid plastics (without any fillers)are poured in, and usually simple geometry is produced with a distinctive lustrous appearance. The process is inexpensive, however it is limited to relatively simple shapes. Small radio cabinets and ornamental objects are commonly made by plastics casting.

It was realized that the shell casting technique could be applied to suppress the dimensional inaccuracy and surface roughness, typical of **sand-casting metallics**. Firstly, the metallic pattern is heated to a temperature of 180 - 370 °C. When the moulding material (a mixture of sand and heat-setting resin) is packed around the heated pattern, the resin sets, binding the sand into a thin shell (4 – 10 mm) that reproduces the pattern precisely (with tolerances up to 0.08 mm). This shell, reinforced by a backing material, then becomes the mould, Fig 3.7. The gates, sprues and risers are incorporated within the shell. After pouring, solidification and cooling of the product, the shell is broken during the removal operation. The heat transfer conditions are radically different from thick sand moulds, as the control of heat transport is more feasible.

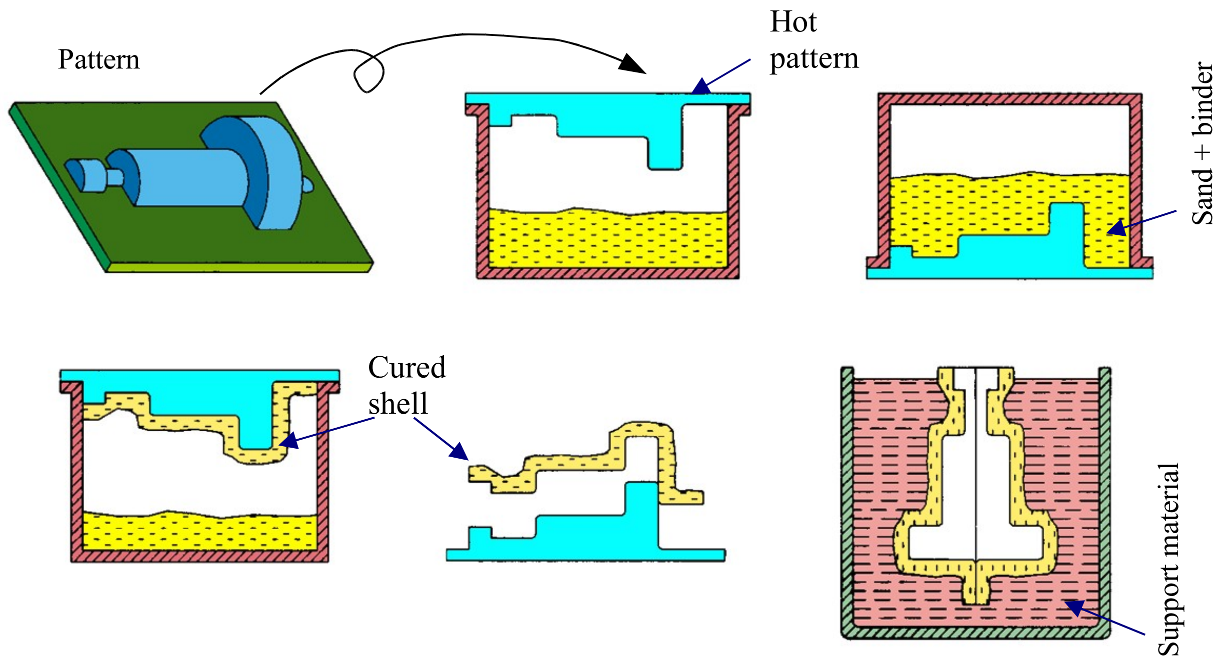


Fig 3.7: Shell-mold preparation [329, 525, 575]

Other shell materials can be applied, e.g. a **mixture of sand and sodium silicate**. This mixture is packed around the pattern and hardened by blowing CO_2 through it (using a gassing head). Within 10 seconds, the sand becomes strongly bonded as the sodium silicate transforms into a stiff binder. Silicone parting agents should be sprayed on the patterns to prevent sticking.

A further development of shell-mould casting is the technique where composite shell moulds are made of two or more different materials. Composite moulds combine for example, a shell mould with a graphite mould and may include the intricate cores and chills to cast impellers for turbines.

Shell-mould casting is suitable for automation (definitely more than the sand casting method, where human involvement is in producing the inner walls of sand moulds). The pattern is permanent and the shell material can be recycled. The process has proved practical for parts ranging from malleable iron chain hooks to automotive cranknkshafts. Shell moulding is especially suitable for producing the high-precision cores.

Typical products include small parts requiring high precision, such as cylinder heads, gear housings and transmission drums. The shell-mould method is suitable for almost all castable metallics.

A gold sculpture of Mickey Mouse over 0.6 m high and over 45 kg in mass valued at more than US$1 million.

** ** ** ** **

Acknowledgements: This file is created by compilation and adjustment of data from a number of sources: [28 – 30, 229 – 231, 329, 431, 475, 478, 524 – 530, 573 - 575]

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