Chapter 9

Investment Casting

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Investment casting, or, as the process was originally known, the lost-wax process, has been practised virtually for as long as historical records exist; examples can be traced to the Shang Dynasty, *circa* 1715 BC and long before. The term 'investment casting' is derived from the meaning of the word 'invest' — to clothe (or envelop), hence the investing or clothing of the pattern in a refractory material.

The growth of the investment casting industry stems from the early 1940's when the necessity for complex close tolerance components for the aerospace industry and for armaments resulted in the development of the process as used by the dental industry. Since that time investment castings have found an ever widening field of application in the aerospace and general engineering industries.

Basically, the process consists of the production of an expendable pattern from a die, investing or coating of the pattern with a suitable refractory material, removal of the pattern (which is expended or destroyed at this stage) curing or firing of the mould, followed by casting of the metal and subsequent knock-out of the casting(s) from the mould. Figs. 1 and 2 illustrate the process as applied in the ceramic shell and block mould techniques.

This chapter relates specifically to the production of investment castings for the general engineering and aerospace industries. Reference will not therefore be made to the art, dental and jewellery trades in which the process is still widely utilised.

The investment casting process affords the designer a virtually unlimited freedom of design for cast components with an excellent surface finish and a high degree of dimensional accuracy. Investment castings, which are now established as reliable engineering components, are manufactured to agreed specifications with the backing of quality control procedures.

Fig. 1. *The ceramic shell process.*

Pattern die

Wax assembly

Investing the pattern

Stuccoing

Dewaxing

Casting

Knock-out

Finishing

PATTERNMAKING

The expendable patterns utilised in the investment casting process are produced from dies which split or part to facilitate removal of the pattern from the die. The pattern material is normally injected into the die, under pressure, by an injection machine. Numerous injection machines of varied design and complexity are available from equipment manufacturers. The more complex machines incorporate temperature control in the pattern material reservoir and pressure control at the injection nozzle.

Pattern dies range from dies produced in silicone rubber for the production of prototype very small quantity patterns, to complex multi-part dies machined from solid metal, from which many thousands of patterns are produced. The majority of pattern dies in use today are machined metal dies manufactured from steel and/or aluminium alloy. The choice of die material and method of manufacture are largely governed by the required die life, *ie* the number of patterns which can be produced before any significant reworking of the die, and the dimensional accuracy required of the patterns. One-off patterns and short run prototype patterns, of a development nature, can be produced from cast dies; the die material being cast around a master pattern, the master being a replica of the pattern required. Materials for cast dies include rubber, plaster, epoxy resin and the low melting point metals such as the tin-bismuth alloys. The use of soft metal dies faced with hard metals, by metal spraying, and dies produced by the electrodeposition of hard metals onto a master pattern and backed by soft metal or resin, have found some application. An allowance to accommodate the liquid and solid contraction of the metal to be cast must be incorporated in the pattern. Thus the pattern die must carry this metal contraction allowance and any additional allowance required for contraction of the pattern material.

Simple 'cast' dies, in epoxy resin or tin-bismuth alloy, may cost from thirty to sixty pounds. Metal pattern die costs vary from a few hundred pounds for a relatively simple die in aluminium alloy to thousands of pounds for a complex die machined from hardened steel.

Pattern materials
The majority of patterns utilised at the present time are produced from wax with or without the addition of resins and filler materials. Other pattern materials which have been used from time to time and which in certain cases still find a limited application, include frozen mercury, soft metals, mixtures of organic and inorganic salts and urea. Polystyrene has found some favour as a pattern material and recent statistics for the industry would indicate that polystyrene accounts for some five per cent of patterns in use; the remainder, to all intents and purposes, being wax.

Pattern waxes may be broadly classified into four groups: natural waxes, mineral waxes, synthetic waxes and paraffin waxes. Natural waxes include beeswax and a variety of vegetable waxes and some resins. Of these, only the Carnauba
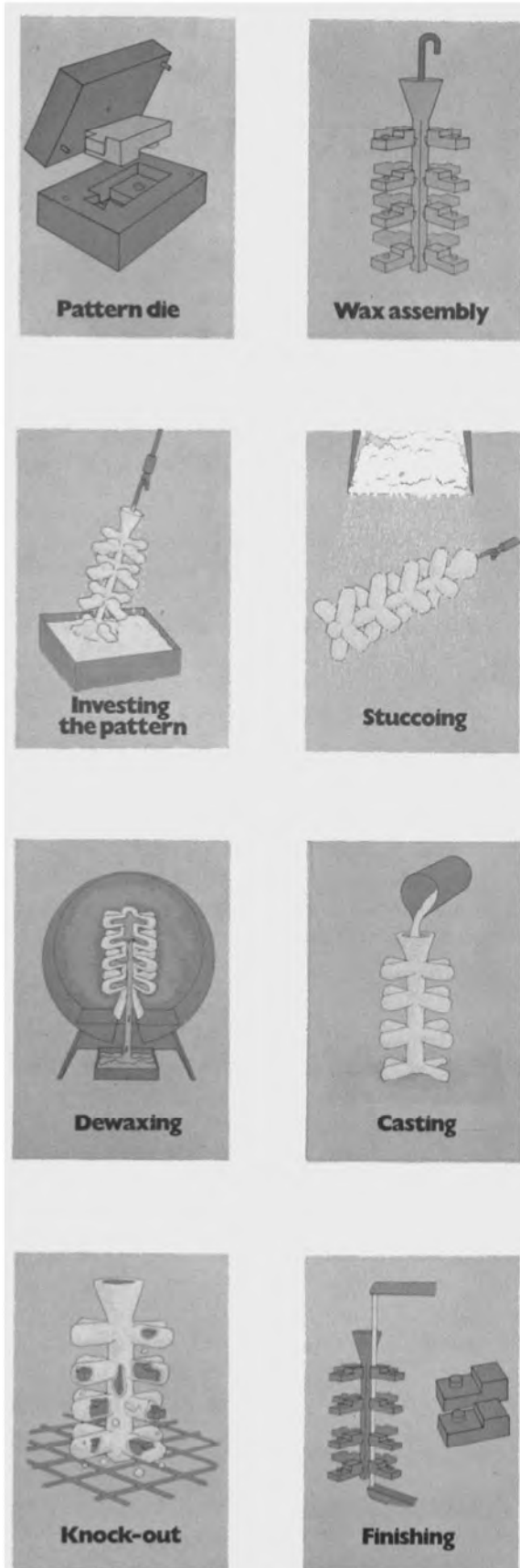
and the Candelilla vegetable waxes, derived from vegetation in the South Americas, are of any real importance to the industry at the present time.

Mineral waxes are extracted from coal and similar deposits, *ie* peat and shale, the predominant one being Montan wax derived from brown coal or lignite found in East Germany. Synthetic waxes, as the name implies, are a product of the synthesis of soft fats and fatty acids. Microcrystalline waxes, derived from petroleum, have found a wide application. In the majority of cases, pattern waxes used commercially are a special blend of one or more of the available wax types.

The satisfactory production of patterns for the investment casting process requires that the pattern material shall be sufficiently fluid on injection into the die to ensure accurate reproduction of detail. It must possess low contraction characteristics to minimise shrinkage in the pattern die and have sufficient mechanical strength to withstand handling and, possibly, storage. A low ash content is vital to minimise contamination of the mould after removal of the pattern.

The predominant routine controls applied to wax pattern materials are tests for the following properties: melting point, congealing point, ash content, resistance to penetration and viscosity. Increasing attention is being devoted to 'behaviour' tests, *ie* the performance of the pattern material in use; behaviour tests include shrinkage, dimensional stability and reproducibility, mechanical strength and setting-time compatible with removal from the die and subsequent handling.

Pattern assembly

Since a large number of the investment castings utilised by the general engineering industry are relatively small, falling within a weight range of from a few grammes to one kilogramme, it is practice to assemble a number of individual patterns around a single running system. However, where larger castings are concerned, for example for the aerospace industry, the production of single castings in individual moulds is not uncommon.

MOULD MANUFACTURE

Two distinct processes are utilised for the production of moulds in the investment casting process, namely the ceramic shell process and the block mould process. The two techniques are represented schematically in Figs 1 and 2 respectively. The ceramic shell process is widely used for the production of the larger investment castings in steel, nickel and cobalt-base alloys and other high melting point materials. The block mould process finds application in the production of small and medium sized castings and in the light alloy field.

The ceramic shell process

The pattern assembly, incorporating the pattern or patterns, the running and feeding system and the pouring cup as a single unit, is dipped into a primary slurry or dip-coat.
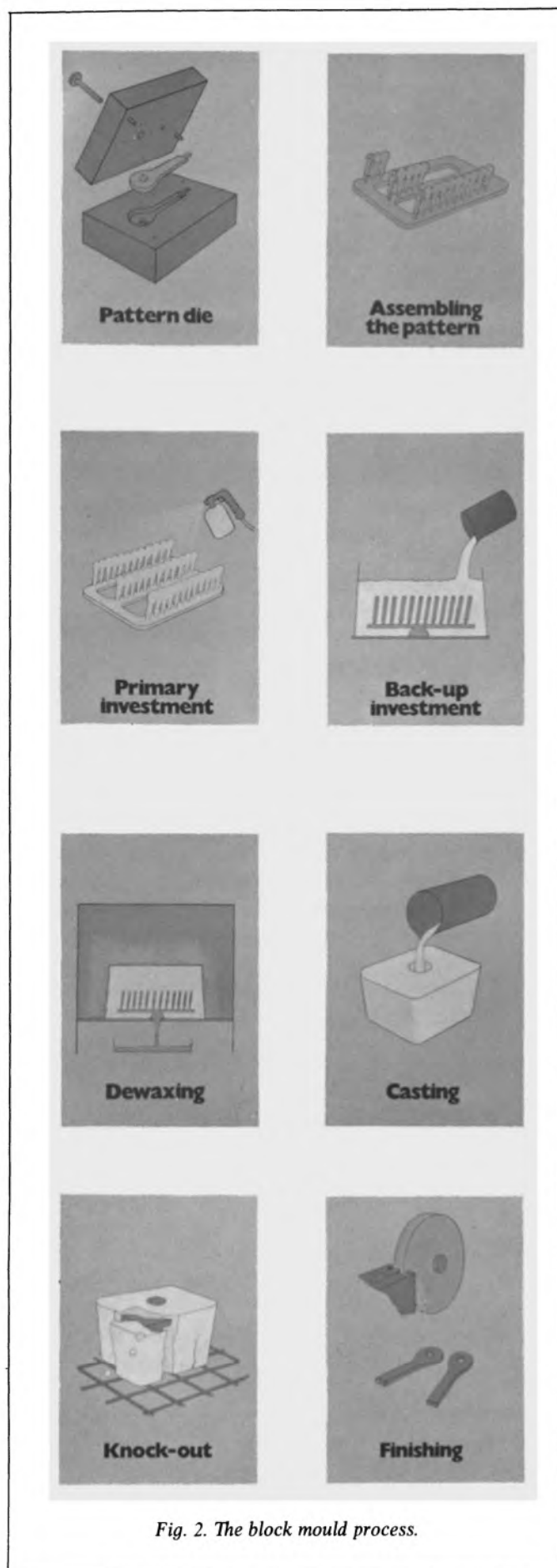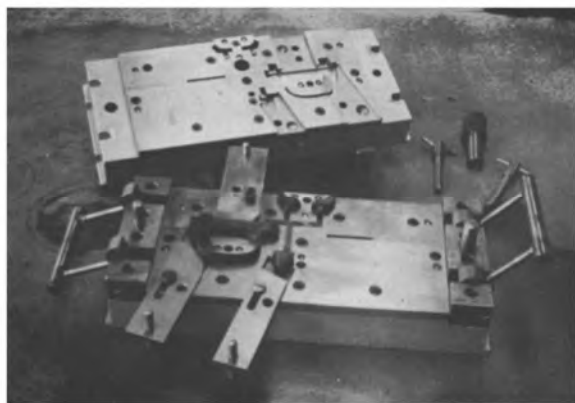

Fig. 2. The block mould process.

Machined metal die, the wax pattern produced is seen in the die half in the foreground. (Courtesy of BSA Precision Castings Ltd.)

Completed wax pattern assembly. The operative is checking the weight of the assembly which comprises 60 individual patterns. (Courtesy of BSA Precision Castings Ltd.)

Application of the primary dip-coat slurry by dipping the pattern assembly. (Courtesy of BSA Precision Castings Ltd.)

After draining-off the excess slurry from the pattern, the initial coating of refractory aggregate, the primary stucco, is applied. The primary stucco is usually applied by a 'raining' technique (placing the assembly in a stream of refractory particles) however, fluidising, ie immersion of the assembly in a fluidised bed of refractory, is sometimes used. The refractory particles key to the wet primary slurry and the coated assembly is dried or chemically set. A secondary dip-coat or slurry is applied, followed by a further application of refractory particles onto the wet secondary slurry and then drying or hardening. Both techniques of refractory application, ie 'raining' and the use of a fluidised bed, are utilised by the industry. However, the severity of fluidising, resulting in penetration of the primary dip-coat by particles of refractory, thus destroying the quality of the mould surface, has led to the introduction of a combined technique — 'raining' for the primary refractory or stucco and fluidising for the back-up coats. The ceramic shell process involves the following sequence of operations: application of dip-coat or slurry, application of refractory, and then drying or hardening; this sequence is repeated until a refractory shell of sufficient thickness has been built up around the pattern assembly. It is normal to apply between six and eight separate shell coats giving a refractory shell or mould wall thickness of from 6 to 12 mm.

Mould materials – binders
The binders, which provide the 'green' and fired bond in ceramic shell moulds, are contained in the primary and secondary slurries or dip-coats. The range of binders available includes ethyl silicate, sodium and potassium silicate, silica sols and a number of miscellaneous binders such as the ammonium, sodium and aluminium phosphate types. Of these, recent figures for the UK industry would indicate that ethyl silicate, silica sols and the soluble phosphates of sodium and potassium are predominently used.

Ethyl silicate. Ethyl silicate is formed by the reaction of silicon tetrachloride with ethyl alcohol — $SiCl_4 + 4C_2H_5OH \rightarrow (C_2H_5O)_4Si + 4HCl$ — and has a silica content of some 28 %. With the presence of water in the alcohol, hydrolosis and subsequent condensation results in an ethyl silicate of approximately 40 % silica content.

Silica sols. In the silica sols, the silica is present as a suspension of fine particles of silica in water. The silica content of the sols can be as high as 30 %. Gelation of the silica sol or hydrolysed ethyl silicate, forming the bond in the dip-coat slurry, is controlled in the main by the pH value of the solution. Fig. 3 shows the relationship between gelation time and pH value for silica systems and that the optimum gelation time, ie the least time for setting, occurs with a pH value of between 5 and 6. Control of pH value of dip-coat slurries is therefore practised to give optimum setting or gelling conditions.

A primary requisite of an investment casting process dip-coat slurry is stability, in terms of both pH value (to avoid premature or protracted gelation) and dispersion of the filler material. Routine controls for dip-coat slurries include pH value, viscosity and filler dispersion.

Refractories
Refractories used in the manufacture of ceramic shell moulds include: for primary investments — molochite (calcined china clay), alumina, fused silica and zircon; and for secondary investments — mullite, alumina, molochite, fused silica, calcined fireclays, natural silica and zircon. Primary investment materials are finely ground flours of − 200 mesh size whilst secondary investments range up to a size of − $\frac{1}{4}$/ + 120 mesh size.

A recent survey of refractory materials used by the UK industry would indicate that molochite, in various size gradings, and a blend of zircon, sillimanite and alumino silicate account for the bulk of refractory material used. Control tests applied in the manufacture of ceramic shell moulds include tests for permeability, thermal expansion and mechanical strength in both the 'green' and fired state.

Dewaxing
Whilst numerous methods are available for the removal of

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Application of the stucco in a fluidised bed of refractory (ceramic shell process). (Courtesy of BSA Precision Castings Ltd.)

Dewaxing the ceramic shell moulds in a steam autoclave. (Courtesy of BSA Precision Castings Ltd.)

Casting the fired ceramic shell mould (the indirect arc furnace has been rotated through 180° to cast the mould, ie the Durville method of casting). (Courtesy of BSA Precision Castings Ltd.)

the pattern from the 'green' mould. *eg* solvents, hot liquid and hot air, the two most common techniques in use today are flash dewaxing and autoclaving. Both of these latter techniques provide an immediate and rapid heat input to the mould, melting the pattern material which drains away. The steam autoclave has found a wide application for the dewaxing of ceramic shell moulds. Flash dewaxing involves the placing of the moulds in a furnace standing at 1000°C.

During dewaxing the rapid application of a sufficient heat input to the surfaces of the pattern assembly is of prime importance, since the surface layers must melt and drain away, allowing room for the expansion of the bulk of the pattern which would otherwise result in damage to the 'green' mould.

The block mould process

Whilst variations of the block mould process are used, the basic process involves the production of a monolithic refractory mould usually referred to as a block or solid mould. The monolithic mould may be produced by a single or double investment. In the latter case a primary investment is applied to the pattern assembly, either by spraying or dipping, followed by a stucco of relatively coarse refractory particles. The coated assembly, after drying, is placed inside

a suitable container and the second investment is poured around the coated assembly. Dewaxing of the mould is carried out at relatively low temperatures followed by firing prior to casting.

Monolithic moulds still find an application in the production of investment castings in steel and high alloy materials. For the production of light alloy castings monolithic or block moulds in plaster are widely used; a major advantage of plaster block moulds is that they are highly insulating, allowing extremely thin wall sections to be cast, in some instances down to 0.5 mm.

METAL MELTING AND CASTING

Metal melting for investment cast alloys may be conveniently divided into the following groups: for ferrous materials, *ie* steels and high alloy materials, indirect arc and induction furnaces are predominantly used. For non-ferrous alloys reverberatory furnaces and crucible type furnaces are predominantly used. Vacuum melting has become established within the industry in recent years for the melting and casting of the high temperature and other special alloys. A casting technique applied to both indirect arc and induction melting is the Durville process. This involves the clamping of an inverted mould on top of the furnace, the mould runner cup being aligned with the pouring lip of the furnace. On casting the furnace is rotated through 180° and the metal enters the mould with a minimum of turbulence, oxidation and air entrainment.

INVESTMENT CAST ALLOYS

Investment castings are available in a wide range of the metals and alloys in use today, including the following materials, all of which are currently produced:

a. Carbon and low alloy steels.
b. Copper-base and light alloys.
c. High alloys steels.
d. Special steels, *eg* precipitation hardening steels.
e. Nickel and cobalt-base alloys.
f. Vacuum melted alloys.

Fig. 3. *The influence of pH on the gelation time of silica systems.*

LOG GEL TIME

pH
0 1 2 3 4 5 6 7 8
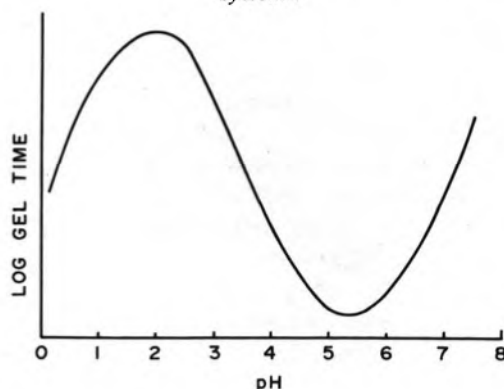
British Standard Specification 3146, Part 1, 1959, covers carbon and low alloy steels. British Standard Specification 3146, Part 2, 1961, covers high alloy steels, nickel and cobalt-base alloys for investment casting.

Investment castings are manufactured to strict quality control procedures and many of the established foundries are fully approved by the relevant government and civil inspection authorities.

DIMENSIONAL ACCURACY AND SURFACE FINISH

In considering the dimensional accuracy achieved by the investment casting process, it is relevant to mention the process factors which will affect the accuracy of the castings produced. These may be summarised as follows:

i. Contraction of the pattern in the die.
ii. Mould contraction on drying and expansion on dewaxing and firing.
iii. Scaling, shrinkage and distortion of the metal cast, in cooling to room temperature.
iv. Scaling and/or distortion during post-casting operations.

These process variables are counteracted by careful control of raw material quality and by stringent process control through all stages of the manufacturing cycle.

Tolerances – linear dimensions. In general, an as-cast tolerance of ± 0.13 mm per 25 mm will apply for linear dimensions. Where smaller dimensions are concerned, up to 13 mm, a closer tolerance of ± 0.1 mm will apply. In certain cases, generally confined to dimensions of the order of 6 mm, a tolerance of ± 0.08 mm can be achieved, however since this level of dimensional accuracy may call for specialised tooling and closer control of production techniques, a consequent increase in component cost may be incurred.

Radii. A normal tolerance for cast radii is ± 0.40 mm per 25 mm of radius. This tolerance is applicable to both internal and external radii.

Straightness. Whilst straightness will depend upon the overall dimensions of the component concerned, as-cast straightness will at least be held within a tolerance of approximately $\pm 1.0\%$ of the length in question, as indicated in Table 1.

Angles. The accuracy of cast angles will depend to a large

Fig. 4. *Maximum depth of through and blind holes practical in investment castings.*
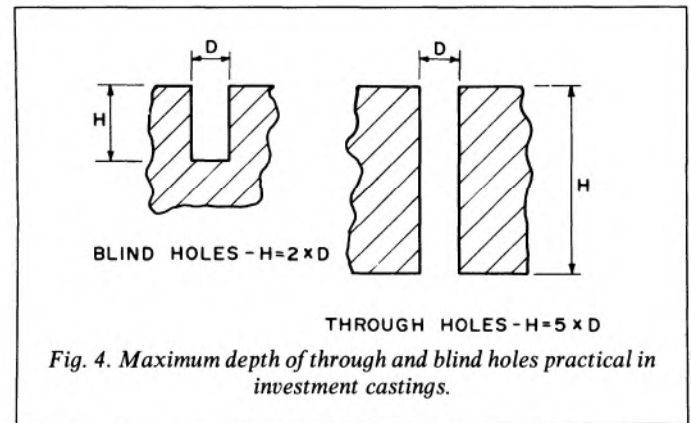
extent upon the configuration of the component, however a tolerance band of $\pm 0.5°/\pm 1.0°$ will generally apply.

Cast holes. The investment casting process enables holes of various shapes to be cast-in. A tolerance of ± 0.13 mm will apply to the diameter and depth of cast holes, up to a diameter of 25 mm. There is, however, a restriction on the depth of blind and through holes in relation to their diameter as indicated in Fig. 4. The use of preformed cores enables extremely small holes of considerable length to be accurately cast.

Surface finish. The as-cast surface finish of investment castings is a major attribute of the process. Table 2 gives average surface finish ranges for investment castings shown alongside, for comparison, the surface finish ranges for the material in the machined condition. It must be remembered, however, that unlike a machined surface the as-cast surface is not necessarily consistent in terms of the pattern of 'peaks' and 'valleys'.

Table 1. *Investment casting tolerances — straightness.*

Dimension	As-cast tolerance: Straightness
up to 50 mm	± 0.50 mm
50–150 mm	± 1.0 mm
greater than 150 mm	± 1.5 mm

Plaster Molding

Plaster mold casting is a specialized casting process which is highly adaptable to the production of nonferrous castings*–particularly aluminum, zinc and magnesium as well as gold and silver. Plaster molded castings are capable of producing intricate surface detail. They offer greater dimensional accuracy than many other casting processes and allow the casting of thin metal sections not possible with other methods. The four generally recognized plaster mold processes are:

1. Conventional plaster molded castings.
2. Match-plate pattern plaster molded castings.
3. The Antioch process.
4. The foamed plaster process.

Castings made in plaster molds are more expensive than those made in sand molds. Therefore, plaster mold processes are used only when acceptable results cannot be obtained by sand casting or another less expensive casting process. Intricately designed impellers, components of electronics gear and molds for some types of rubber tires are examples of parts that are produced by plaster mold casting. If these parts were cast in most other types of molds, machining costs would be exceedingly high. Although about 90% of the plaster mold castings weigh less than 20 lbs. each, castings weighing as much as 75 lbs. are produced in substantial quantities and some weigh considerably more. An aluminum alloy casting weighing 4,000 lbs. has been successfully cast in a plaster mold.

In all of the processes for making plaster molds and cores, the principal mold ingredient is calcium sulfate. This is usually compounded with various types of fibrous and refractory aggregates such as fibrous talcs which serve to increase the strength of the mold in both the green and dry state as well as increasing permeability and helping to control expansion characteristics. Small amounts of finely ground silica, pumice stone, clay or graphite may also be added to the mixture. Silica or zircon sands may comprise up to 50% of the material for some plaster molds. Water is then used for converting this mixture to a pourable slurry. Plaster cores are used with plaster molds and are generally made of the same material. Cores may also be made of other materials such as the use of shelled-molded cores. Cores for the match-plate plaster mold process are generally made of sand.

*The sulfur of the gypsum reacts with ferrous metals poured at their higher temperatures and produces very poor cast surfaces.

Characteristics of Calcium Sulfate

Calcium sulfate exists as two different hydrates and also in an anhydrous form. In its dihydrated form ($CaSO_4 \cdot 2H_2O$) it is known by chemists as gypsum. When heated above an equilibrium temperature of 262F (127.8C) gypsum looses three fourths of its water to form the hemihydrate ($CaSO_4 \cdot 1/2\ H_2O$) which is plaster of paris. When the plaster of paris is heated above an equilibrium temperature of 325F (162.8C) all of the water of crystallization is removed and anhydrous calcium sulfate ($CaSO_4$) is formed. The above temperatures are based on laboratory studies of pure calcium sulfate under equilibrium conditions. Temperatures at which the hydrates are formed depend greatly on vapor pressure. For practical purposes, temperatures well above equilibrium temperatures are generally used.

If it is exposed to moisture at a temperature lower than 212F (100C) the anhydrite formed near 325F (162.8C) will absorb water and will revert to the hemihydrate. The anhydrite produced by heating to above 1000F (537.8C) will absorb water less rapidly. Similarly, when plaster of paris (the hemihydrate) is mixed with water, gypsum (the dihydrate) is re-established yielding a coherent solid in a few minutes. This reaction is called "setting." Prolonged exposure of the hemihydrate to moist air at temperatures below 212F (100C) results in a slow conversion to the dihydrate. Commercially, all three forms of calcium sulfate are sometimes referred to as gypsum.

Gypsum for foundry use is generally available in varying grades—the "white molding plaster" is a specially formulated product containing white plaster and a refractory material to give greater strength and dimensional accuracy after the water has been removed during "burn-out." This grade has been specifically designed for the production of aluminum matchplates, cope and drag sets, core boxes and loose patterns. This material has ample strength for handling and may even be carved.

Another grade of gypsum for foundry use is similar to the above, except for the addition of fine foundry sand. This material is used where additional chilling (to accelerate solidification) may be required. An expansion plaster for fabricating expanded patterns, models and molds has also been available. This industrial tooling and patternmaking gypsum cement possesses unique characteristics. The medium high expansion grade is capable of expanding uniformly in all directions and has the highest setting expansion of any known gypsum cement. Expansion values can be controlled by the quantity of water used in the mixture. Through the use of proper water-to-plaster ratios, expansion values from 1/16-inch to 3/16-inch per foot are possible. These expansion plasters may be used wherever patterns, matchplates and models with shrink allowances are fabricated. For example,

expansion plasters are used for core drier patterns by making a cast (or impression) from the pattern. Then, after the plaster cast expands to the desired over-sized dimensions subsequent gypsum patternmaking operations are used to complete the pattern. As an example of a typical use of the expansion plasters, a matchplate producer uses the expansion plasters to add the extra shrinkage allowance necessary in a wood matchplate which will be reproduced in aluminum by pressure casting. (See pressure matchplates page 127).

Patterns and Core Boxes
Patterns and core boxes for plaster mold casting are commonly made of metal (aluminum alloy, brass or zinc alloy). Flexible rubber patterns are widely used for producing intricate molds. Cast epoxy resin patterns may also be used. For instance when duplicate patterns are required, they can be made quickly by molding them from epoxy resin in metal master dies. Because patterns for production of castings by plaster mold processes must withstand repeated exposure to liquid slurrys, wood patterns must be sealed or they will swell and distort. Wood patterns may be used for producing small quantities of plaster molded castings, and are used as matchplate pattern molds.

Although proprietary release agents are available, release agents may be formulated using a low viscosity mineral oil emulsified with wax and water. Flake graphite or mica mixed with a paraffin-base oil can also be used. Other common forms are stearine, soft soap or waxes in a suitable solvent, light oils or emulsified oils. The stearine parting agent is prepared by melting down 1/4 lb. of stearine and after removing it from the heat, adding 1-pt. kerosene. This material is now brushed (or may be sprayed) over the pattern. Patterns should be coated *lightly,* and if brush marks show, the release agent should be thinned out. A heavy coating will penetrate the plaster resulting in a poor cast metal surface, or will reduce sharpness of detail.

Gating Systems
The gating systems for plaster mold casting are much the same as those used for sand mold casting. However, because of the insulative value of plaster molds, the gates, sprues and runners usually can be smaller in plaster molds because of the lower heat capacity of the mold. Insulating riser sleeves are often used to prolong solidification of the riser, and in turn, to prolong feeding from the riser. As is true for other casting processes, some experimentation and resulting change in the gating system is often necessary to obtain sound castings. For producing a few castings or in attempting to establish an optimum gating system for a production run, a common practice is to cut the sprues and gates in the mold by hand after the plaster

sets, but before it dries. When the most appropriate gating practice is established for a job, the gating system should be made part of the pattern.

Chills

Chills (usually of metal) are often used in plaster molds, where they serve the same purpose as in other types of molding — namely, they help to establish the required thermal gradients in the mold, and improve mechanical properties of the cast metal by increasing the cooling rate. Chills are placed around the pattern in predetermined locations just before the slurry is poured. They are locked in place in the mold when the slurry sets, and are thus less likely to be moved out of position than in the regular production of sand molds.

Flasks

Flasks are usually made of low-carbon steel. They vary in size in accordance with the size of the pattern, the number of identical molds to be produced and the number of patterns in a flask. When the flask is to hold only one pattern half, especially when only a few molds are required, a simple bottomless flask is placed on a mold board and the pattern half is positioned within it on the board, ready to receive the slurry. When many identical molds are required, especially when two or more patterns are placed in a single flask, a flask with a flat bottom that serves as a mold board is used. The pattern halves are arranged on the flask bottom. However, in the Antioch process, for small single-pattern molds, the pattern and flask are often an integral unit. (See Antioch process, page 137).

The flask for a given application should be large enough to allow space for the same thickness of plaster surrounding the pattern as would be needed if the mold material were dried sand. Standardization of flask sizes is important in production operations because this simplifies tooling, especially when vacuum pouring is used. Standardization of flask size is also desirable for pouring the slurry and drying of the molds.

In the production of plaster molds (Fig. 56) the plaster of paris is mixed with a relatively high proportion of water, in the range of 120 - 180 parts of water to 100 parts of plaster (by weight). It is important to remember that the consistency of plaster formulations will vary. Generally speaking, the use of more water results in lower and green and dry strength, higher permeability and lower expansion. Basically, ten parts of a metalcasting plaster to 14 parts of water would be a starting point. Carefully weigh all of the ingredients and use water at 110F (43.3C). Water used in mixing plaster should be as pure as possible. In many cases, water for industrial use is taken from contaminated sources and is high in organic impurities that will lengthen the setting time of the plaster. Large amounts of soluble salts e.g.

sodium chloride, sodium sulfate and magnesium sulfate in the water can migrate to the surface of the mold during drying. The resulting efflorescence forms hard spots on mold surfaces that can result in clay-sticking or other mold problems. Use either hand or power equipment for the mixing of the slurry. Usually a round-bottom vessel similar to that used by bakers for mixing dough works well for plaster. Always *add the dry mix to the water*. Scatter the preweighed amount of plaster into a weighed or measured amount of water. Allow the plaster to soak one to three minutes to become thoroughly wetted before mixing. Mechanical mixing is recommended for uniform densities. Mix the plaster from two to three minutes, or until the plaster starts to cream. A two or three inch, three-blade standard pitch propeller rotating at 1750 rpm is recommended. Direction of the rotation should force the slurry downward. Mixing bucket dimensions should be such that the depth of slurry is 1-1/2 to 2 times the diameter of the bucket. Mixing of large batches or delays in pouring should be avoided. The plaster slurry or mixture of a creamy consistency free of lumps is now poured over the pattern, or into a core box where it is allowed to set, forming a solid mold or core composed of gypsum with free water distributed throughout.

Remove the plaster part from the core box or pattern with extreme care to avoid marking or breakage. One method is to insert a thin wire through the partially set plaster to the pattern, then when the plaster has set, blow compressed air gently through the hole. Another is to start wedges at the parting line and separate the plaster from the pattern with the aid of compressed air. Remove the flexible patterns by forcing compressed air between the pattern and the mold. To release the plaster from the core box or pattern mechanically, form a bridge with draw spikes and a horizontal piece. Wrap upward with short light blows.

The set mold is dehydrated by heating the mold for a sufficient length of time (depending upon the size and shape of the mold). This is done in ovens, and various drying temperatures are used depending upon the particular plaster molding process. The most practical means of removing free water is to heat the gypsum for a sufficient length of time at a temperature between 212F (100C) and 262F (127.8C) usually at approximately 250F (121.1C). Higher heating temperatures may be employed ranging from 400F-1400F (200C-760C). Complete dehydration is necessary to liberate the free and chemically combined water since the presence of even minute amounts of water in the mold at the time of casting would result in imperfect castings. The heat of the molten metal would convert any water present into steam which cannot readily escape because of the low permeability of this type of mold, and this would result in rough surfaces and blow holes in the casting.

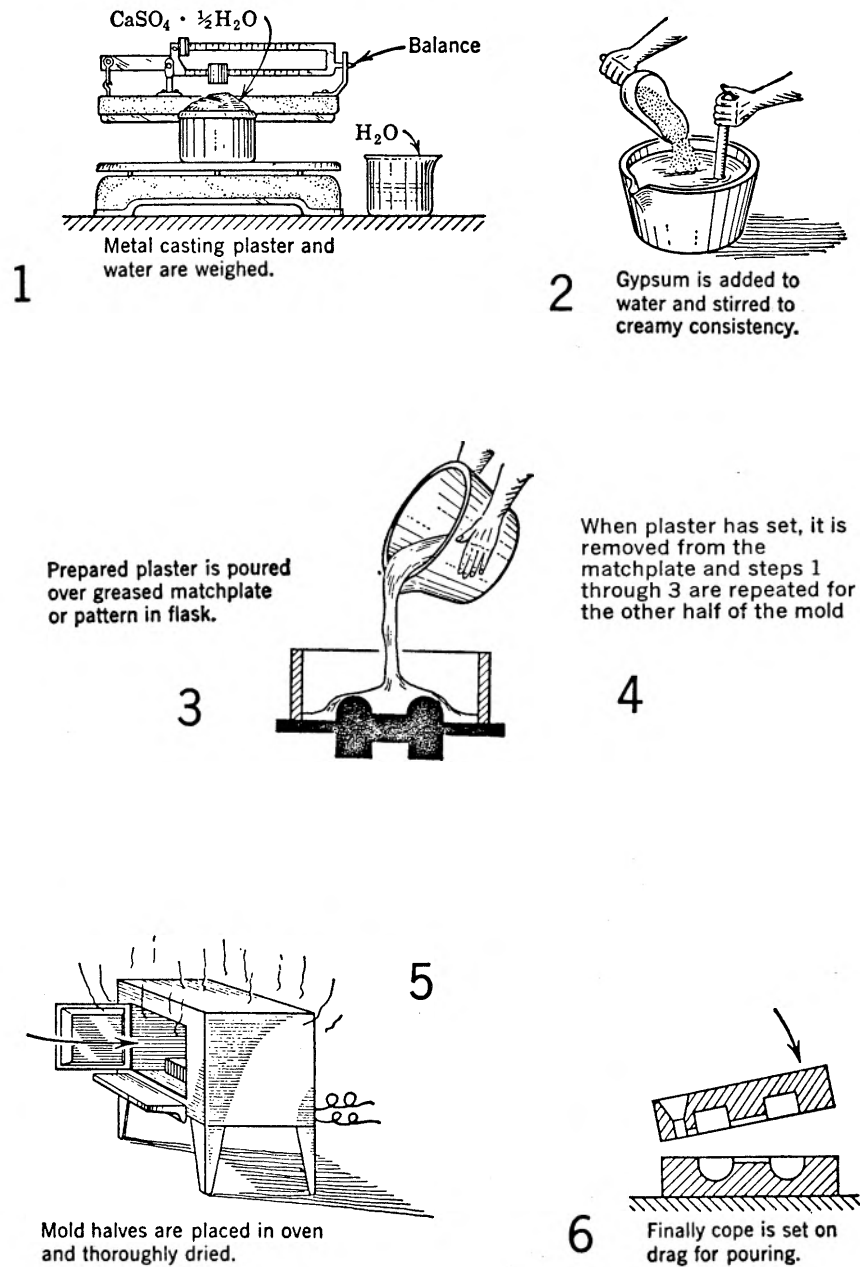Drying of the mold is one of the most important operations in successful

$CaSO_4 \cdot \frac{1}{2}H_2O$

Balance

H_2O

Metal casting plaster and water are weighed.

1

2 Gypsum is added to water and stirred to creamy consistency.

Prepared plaster is poured over greased matchplate or pattern in flask.

3

When plaster has set, it is removed from the matchplate and steps 1 through 3 are repeated for the other half of the mold

4

5

Mold halves are placed in oven and thoroughly dried.

6 Finally cope is set on drag for pouring.

Fig. 56—Making a plaster mold.

plaster mold casting. Many drying methods can be used successfully, but all require a source of heat and air circulation. Most plaster foundries use gas or oil fired furnace with a recirculating air and exhaust system. Electronic controls are used extensively to minimize difficulties resulting from improperly dried molds. Oven temperatures are often controlled thermostatically at 800F (426.7C) during the drying cycle which may range from 16 to 36 hours depending on the type of molds being dried. The drying cycle is controlled by thermocouples placed at strategic locations in the oven. The drying of plaster molds — often referred to as mold "burn-out" — is critical, because in general, a higher burn-out temperature results in greater burn-out shrinkage. Drying rate depends on oven temperature, air velocity and humidity, mold thickness and oven load.

Higher temperature drying of plaster molds will require furnaces similar to those used for heat treating. However, if these higher temperatures are used, the molds must be cooled to at least 400F (204.4C) before they are removed from the furnace. Dense molds, and those of certain compositions must be furnace cooled to even lower temperatures or they will crack. With a temperature-zoned conveyor furnace, the drying cycle can include the necessary cooling and production can be continuous whereas a batch-type furnace, cooling to 400F (204.4C) or lower means tying up the furnace for a longer period of time and interference with production. Regardless of the type of drying equipment, it should include provisions for discharging both wet air and the by-products of combustion.

Insert
The plaster slurries should be poured into the core boxes or molds immediately after mixing since the setting time is usually about 25 to 30 minutes. Be sure the mold surface is clean and has a smooth surface properly treated with a parting (release) agent. Mechanical vibration, brushing of the slurry on the pattern face and careful pouring will help to eliminate pinholes in the surface of the mold caused by entrapment of air. It is also important to insure that the back surfaces of the plaster mold are flat and level. Failure to have surfaces true and flat may cause movement of plaster molds thus causing oversize castings.

After removal from the mold, the pattern is cleaned, recoated with release agents and placed in a flask for a repeat operation. Frequently, the flask may be removed at the same time as the pattern, but never in the production of plaster molds for match-plate patterns. (See production of cast match-plate patterns, page 127). The released plaster mold is now ready for the drying operation.

The high temperatures employed in the dehydration or burn-out process are accompanied by mold shrinkages ranging from 1-2% depending on the

temperature used. The higher the burn-out temperature, the higher the degree of mold shrinkage. In addition, the strength of the mold as-cast (about 100 psi) is reduced approximately 50% in the burn-out.

Plaster molds have a low heat capacity, therefore solidification rates for castings made in such molds are slow. This slow cooling has both advantages and disadvantages. It permits better feeding, particularly in thin sections. Replication of intricate details would be difficult to obtain with rapid cooling. But, it slows production by lengthening time between pouring and shakeout, and for most alloys, it results in castings of lower strength. The use of chills in specific areas can usually minimize this disadvantage. The solidification rate for a test casting made in a conventional plaster mold is more than four times as long as for one made in a hard-rammed green sand mold. Other process comparisons are shown in Fig. 57.
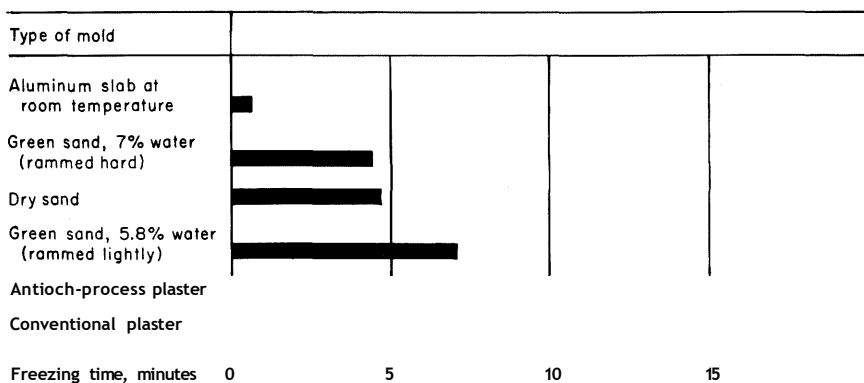
Type of mold				
Aluminum slab at room temperature				
Green sand, 7% water (rammed hard)				
Dry sand				
Green sand, 5.8% water (rammed lightly)				
Antioch-process plaster				
Conventional plaster				
Freezing time, minutes	0	5	10	15

Fig. 57—Comparison of freezing times for identical test castings poured in various types of molds.

Mold Composition
Materials for molds for match-plate patterns are available as proprietary dry mixtures ready for mixing with water. However some foundries prefer to make their own mixtures. A typical mixture for a match-plate pattern mold is shown in the tables below.
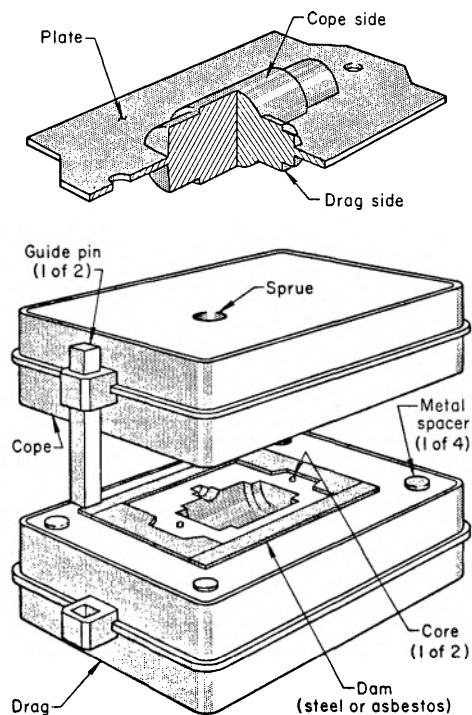
Plate

Cope side

Drag side

Guide pin
(1 of 2)

Sprue

Metal
spacer
(1 of 4)

Cope

Core
(1 of 2)

Drag

Dam
(steel or asbestos)

Fig. 58—Assembly details of a match-plate mold.

Table 3. Typical Composition of Dry Material for Conventional Plaster Molds

Table 4. Typical Composition of Dry Material for Molds for Metal Match-Plate Patterns

A comparison of Tables 3 and 4 shows a significant difference between the composition of conventional plaster molds and molds for match-plate patterns. It will be noted that in conventional molds both white and gray gypsum are used. However, in match-plate pattern molds only a white molding plaster — a pure grade of gypsum — is used. This ensures a smooth mold finish which, in turn, produces the smooth surface required on match-plate patterns.

Set Time and Drying of Molds

A slurry of the type defined in Table 4 will set in 14 to 16 minutes. After the slurry sets the patterns are removed and the molds are prepared for drying. Molds for match-plate patterns, like molds for conventional plaster castings should be dried as soon as possible after the plaster has set. High temperature drying cannot be used for match-plate molds, because it results in unacceptable distortion and size change. Match-plate molds are usually dried at 250-400F (121.1-204.4C) for 12 to 72 hours. Size and section thickness of the molds determine the length of time in the drying ovens. The center of the thickest section of the mold should reach at least 220F (104.4C) before drying is stopped. Permeability of a match-plate mold at this stage is approximately the same as that of a conventional mold.

Metal Selection and Pouring Practice

Match-plate patterns are generally cast from aluminum alloys, most frequently alloys 355 and 356. Other alloys may be used which offer greater ductility and better machinability. The ductility is important in making match-plate patterns because patterns often require straightening. This is more true with the present technology of casting production which uses high pressure (high density) molding techniques.

Because of the low permeability of a match-plate mold, some assistance is required to fill the mold quickly and completely. Pressure assistance is used rather than vacuum, partly because pressure equipment is more adaptable to a variety of flask sizes than is vacuum equipment. The equipment for pressure casting is illustrated in Fig. 59. The first step in its use is to place a
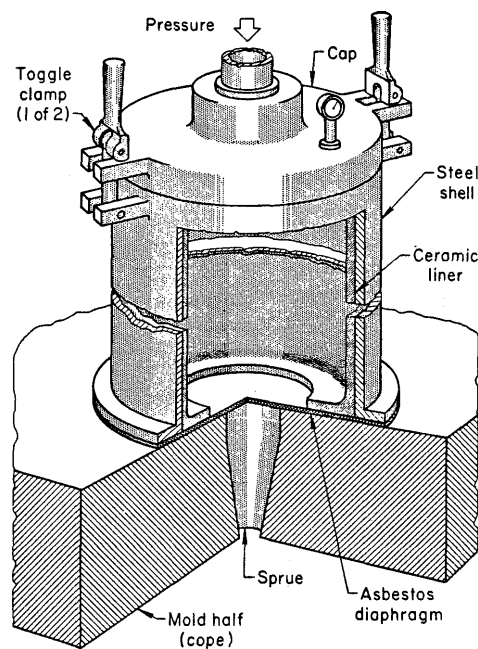

Fig. 59—Cylinder used for pouring a casting with pressure assist.

diaphragm of sheet asbestos (about 1/8 inch thick) over the sprue in the mold. A ceramic-lined cylinder is then placed on the diaphragm as shown in Fig. 59. A predetermined amount of metal is poured into the cylinder and a cap is placed on the cylinder and clamped tightly. This cap is attached to the source of compressed air. After the cap is secured in position, the air valve is opened and air pressure against the molten metal ruptures the asbestos diaphragm and forces the metal into the mold cavity. A pressure of 1.5 to 2.5 psi is kept on the sprue for approximately 30 minutes. Shakeout procedures are generally the same for match-plate castings as for castings of similar size and weight which have been casted in conventional plaster molds. Because the plan area of match-plate castings is large in proportion to the cross-sectional area, the castings are highly susceptible to distortion. When they are distorted to an unacceptable amount, they must be straightened. This is done by a skilled operator with the aid of an arbor press and a few simple press tools.

Defects occurring in plaster mold castings are similar to those that occur in sand castings namely, dross inclusions, gas porosity, cold shuts, misruns and shrinkage cavities. Corrective steps are likely to include changes in pouring practice, in vacuum technique if vacuum is used, in core venting or in the gating system.

Foamed-Plaster Molds

Since plaster molds are dense and have a low permeability, this characteristic can be overcome by using mixtures which have foaming agents pre-blended with the plaster. This type of mixture is known as *permeable metalcasting plaster* or the *foamed-plaster process*, and has been developed to produce mold permeabilities comparable to those obtained with the Antioch Process but without the necessity of autoclaving (see Antioch Process).

The foamed-plaster process offers a means for obtaining greater mold permeability than can be obtained in conventional plaster molds. This gain is achieved by adding foaming agents such as alkyl aryl sulfonate, either to the dry ingredients before mixing, or to the liquid slurry as a separately generated foam mixture. A special method of mixing foams the slurry with many fine air bubbles thus decreasing the density and increasing the volume of the slurry. In general, the applicability of foamed-plaster molds is the same as that of plaster molds made by other procedures as far as composition of metal poured, casting size and casting shape are concerned.

Foamed-plaster molds have smooth surfaces with air cells just below the surface. During setting and subsequent drying of the molds, these air cells become interconnected thus permitting escape of gases as the metal is poured. The permeability of the foamed-plaster mold depends mainly on the volume increase from the addition of air when the slurry is mixed. For most molds, a volume increase of 50-75 percent is recommended. This increase usually results in a mold permeability of approximately 5-15 for dried molds. Some foundries may even achieve 20-25 permeability. (The permeability values mentioned are achieved with standard AFS permeability testing instrumentation. For complete test procedure please consult AFS Mold and Core Test Handbook.)

The relationship of several levels of volume increase to weight and permeability is shown in Table 5. The increase in permeability that accompanies an increase in volume of 75% is the highest that can be allowed for most applications. With greater permeability mold strength becomes unacceptably low. With the degree of permeability developed by increasing the volume of the slurry by 50-75%, it is possible to pour most molds without the assistance of pressure or vacuum. Because the drying temperature for foamed-plaster molds is relatively low, it is possible to retain dimensional accuracy.

Table 5. Relationship of Increase in Volume to Weight and Permeability for Foamed Plaster

Volume increase, %	Weight, lb per cu ft	Permeability, AFS (dried molds)
0	90.8	1.0
50	60.6	5.0
61	57.0	8.5
68	53.8	11.5
76	49.4	16.5
100	46	30.0

Foamed-plaster molds are less capable of absorbing heat than the other types of plaster molds. This deficiency can be partly corrected by adding up to 25% (by weight) of washed silica sand or zircon sand to the slurry. At best, however, the heat absorption rate of foamed-plaster molds cannot be expected to be much different from that of conventional or match-plate plaster molds. The rate and direction of metal solidification can be controlled by chills just as with the other types of plaster molds. Although green strength is low, patterns are designed to be pulled from the foamed-

plaster mold, and pattern withdrawal is seldom a problem. Flexible rubber patterns that have a significant back draft would however, be difficult to withdraw.

Various compositions are used for slurries for the forming of the foamed-plaster molds. Many users use a proprietary formulation that contains the plaster and all other ingredients including the foaming agent. This material is then ready to mix with water to make the slurry. Some foundries have developed their own formulations to satisfy specific conditions. As mentioned above, some of these formulations may contain wash silica sand or zircon sand. The sand can be used to reduce the cost of the mold, or it may be used to increase the heat capacity. Sometimes both silica and zircon sands are used for different sections of the mold in order to take advantage of the different heat capacity characteristics of the two types of sand.

The equipment for mixing the foamed-plaster slurries will vary somewhat with the slurry used. The mixture must be capable of beating air into the slurry and producing air cells no larger than about one/one hundred inches in diameter. Large air cells are undesirable because they break under pressure from the molten metal, resulting in casting defects. Proper mixing can be accomplished with several types of mixers, but regardless of the type of mixer used, the greater the power input, the finer the mold structure (the smaller the air cells) and the smoother the surface of the mold. It will also vary somewhat because of the differences in slurry composition.

There are several alternative plaster casting techniques. A most prominent one is the   which has been highly successful in the application of producing castings with complex shapes requiring fine detail and thin sections. The major advantage of the Antioch Process is that it develops a high degree of permeability in the plaster mold, making it easier to obtain fine detail and allowing any moisture or other gases present to escape. The Antioch Process (U.S. Patent 2,220,703) was developed to overcome the principal limitations of conventional plaster molds and cores without sacrificing the advantages of the plaster mold process.

If undried molds are partially dehydrated and then allowed to rehydrate without being disturbed, gypsum crystals slowly recrystallize into granules about the size of sand grains and the mold acquires a porous structure of relatively high permeability. Recrystallization does not take place at the surface of the mold, because not enough water is present; therefore the surface remains smooth. In addition to the greater permeability developed by the dehydration-rehydration process, the molds produced have greater heat capacity than conventional plaster molds because they are composed of approximately 50% of sand.

Unlike conventional molds, Antioch Process molds do not shrink. In fact, they expand slightly (0.001 to 0.0025 inches per inch during processing). Because of their porous structure, the molds have low dry strength and this characteristic, in promoting early collapse of cores as the casting cools, minimizes hot tears in the castings. For very large molds, the low dry strength sometimes necessitates the use of internal reinforcement which may be achieved with hardware cloth or core rods such as those used in making conventional oil-bonded sand cores. When possible, reinforcement

is avoided because of the difference in expansion between the reinforcing metal and the molding material.

To make molds by this process, water is added to the dry mixture of gypsum, sand, a filler material, talc and sodium silicate in order to make a slurry. The addition of foaming agents to the mixture contributes the necessary material for creating the higher permeability. The foaming agents impart a cellular structure to the bulk of the mold with only a thin smooth skin at the mold-pattern interface. Permeability may also be improved by subjecting the mold to a low pressure (5-20 psi) steam autoclave treatment which effectively takes the calcium sulfate into solution. The calcium sulfate crystallizes out as the mold cools down after autoclaving. The fine crystal precipitate at the surface of the mold, and the coarse crystals crystallize in the center of the mold which cools more slowly than the surface. The coarse center structure is much more permeable than similar sections from molds which have not been given the autoclave treatment.

The slurry is introduced by hose into metal core boxes or cope and drag flasks which have been fitted to special matchplates. The mixture develops an initial set, patterns are drawn, and the mold is assembled in the green condition. After standing approximately six hours at room temperature, the molds are then placed in a steam autoclave at about two atmospheres' pressure. They are then cured in air for twelve hours and finally oven-dried at temperatures up to approximately 450F (230C). Autoclaving develops a special permeable structure in the mold, but greatly reduces the dry strength. The oven-drying cycle drives off the free and combined water. Because of the high mold permeability it is not always necessary to drive off all of the combined water in this process.

After setting, but before the dehydration-rehydration treatment, Antioch Process molds have relatively high green strength. When flexible rubber patterns are used this high green strength permits withdrawal of patterns having a severe back draft without damage to the mold. This characteristic makes the Antioch Process particularly suited to the production of molds for parts having angular, blade-like sections e.g. rotors and nozzles. In addition to the cost, which is high for all plaster molds, the major disadvantage of Antioch Process molds is the long time required for processing them. This ties up expensive equipment for long periods. The dry mixture for Antioch Process molds and cores consists of silica sand, white molding plaster, moldene talc and a small amount of materials such as portland cement for expansion control. A typical mixture is given in Table 6 and is varied somewhat in different foundries. However, once a formulation has been established, it is retained for all castings regardless of their size and shape. Best results are obtained weighing all of the ingredients accurately.

Table 6. Typical Composition of Dry Material for Antioch Process Molds

Ingredient	Weight, lb
Washed silica sand (AFS 50 is typical)	50
White molding plaster	42
Moldene talc	7.5
Portland cement	0.5

Note: Slurry is made by mixing 100 pounds of the above dry mixture with 54 lb water.

As soon as the mixture sets the pattern is removed. Procedures for pattern removal are the same as with conventionally produced plaster molded castings. Usually the flask is removed at the same time as the pattern (often the flask and pattern integral). However, large molds are sometimes allowed to remain in the flasks throughout subsequent mold processing and casting of the metal. This is because of the low dry strength of the Antioch Process

All of the aluminum alloys that can be cast in other types of plaster molds can be cast in Antioch Process molds. Most copper-base alloys can also be cast in Antioch Process molds; however, yellow brass is the copper alloy most often cast. The Antioch Process is seldom used for alloys that must be poured at temperatures above approximately 1900F (1037.8C).

Antioch Process molds are generally poured by gravity using the gating systems that are similar to those used for sand molding. The molds are usually at room temperature when pouring begins. Where difficulty is encountered in replicating fine detail, or where thin sections have not filled properly, vacuum assist can be applied.