Back to Basics: Investment Casting – Part 1

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Introduction

The purpose of this paper is to discuss the investment casting (or 'lost wax') process technology for gold jewellery and, in particular, to highlight the critical stages of processing, which influence the production of good castings. It is relatively easy to pour molten carat gold alloy into a mould and obtain a casting, but it is very difficult to obtain good quality castings without any defects and with a good surface quality.

Investment casting is a complex process of many stages and good casting should not be considered as limited to just the melting and casting steps. Successful casting is strictly dependent on a tight observance of the standard operating procedures and with dedicated care at each production step. To obtain good quality castings for jewellery production consistently and to achieve a high yield or productivity, it is important to take care at each stage of the investment casting process and to follow 'Best Practice'.

Shrinkage on solidification

Metals and alloys undergo considerable shrinkage when they solidify due to the closer packing of atoms in forming the crystal lattice during solidification. Gold jewellery alloys contract about 5% by volume on solidification. The practical consequence of this can easily be seen in ingot casting when a funnel-like depression known as a primary pipe is produced at the top of the ingot as the melt solidifies from the mould wall towards the centre, Figure 1.

When producing investment cast jewellery components, provision must be made for a reservoir of molten metal to act as a liquid metal feed into the casting as it solidifies to counteract the shrinkage effect. For investment casting, the central sprue acts as the reservoir. During dendritic growth of the solid metal crystals (or grains), liquid metal is trapped between the growing dendrite arms and shrinkage porosity, or interdendritic porosity, will form in these positions as it solidifies unless more liquid metal can be fed into the spaces between the growing arms (1,2). This becomes increasingly difficult with alloys that solidify over a wide temperature range and also with certain shapes of castings. Figure 2 shows interdendritic or shrinkage porosity in a vertical cross-section of an 18 carat gold ring, gated at the bottom, where the thinner ring shank had solidified first, cutting off the liquid metal feed to the heavier section at the top of the ring. Adequate feeding can usually be achieved by consideration of gate position and gate dimensions (the gate is the connection between the casting and the central sprue, sometimes also called a sprue).

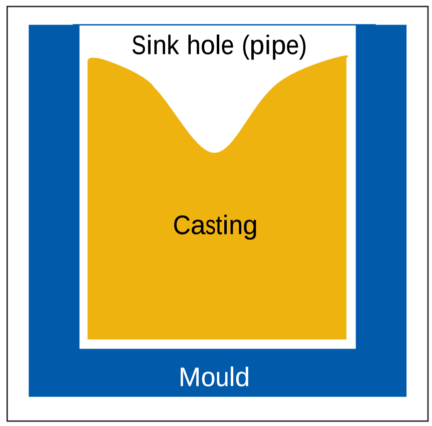

Figure 1 - Shrinkage depression on top of cast ingot

The investment casting process

There are 13 main manufacturing steps in the investment casting process, each of which is important to achieving good quality castings:

1. Design
2. Make the master model
3. Make the rubber mould
4. Make the wax patterns
5. Assemble the waxes on the wax tree
6. Fill the flask with investment to make the mould
7. Dewax the mould (flask)
8. Burnout the mould
9. Melt the alloy
10. Cast into hot flask
11. Remove the investment
12. Cut castings off the tree
13. Finish (assemble, polish, etc)

Figure 2 - Shrinkage porosity in 18 ct gold ring

After casting, and allowing time for solidification, the flask is quenched in water and the investment removed; the cast pieces are cut off the sprue, assembled into jewellery items and finished. In these latter steps the strictly metallurgical variables are little influenced and the formation of metallurgical defects is unlikely, but the finishing processes may expose defects which lay undetected below the surface.

In this first part of the paper, we shall examine the first few stages of the process and highlight best practice (the design of the jewellery is not considered here although it plays a part; some designs are not easily cast).

Making the Master Model

It is important that the model designer has practical workshop experience of the whole casting process; it will help him or her to design castable models easily and economically. The designer should maintain a good relationship with the casting department, in order to understand the design factors that enable castable castings to be produced, and avoiding the likelihood of defective castings and poor yields.

To make the master model, a relatively hard metal is preferable; it assures better finishing, is more wear resistant and less liable to damage. Nickel silver (an alloy of 50% nickel – 30% copper – 20% zinc) is a widely recommended alloy for this use, although other metals or even plastics are used. Sterling Silver is a very common model alloy and even pure silver is used but these do need to be rhodium plated.

The model requires a very high level of finish, i.e. polish, as any surface defects will be accurately reproduced on the rubber mould, and subsequently on the wax patterns and, in turn, on the investment mould and finally on the castings. The removal of these surface defects from castings during the final finishing of jewellery pieces, in order to get the desired quality level, will make finishing more costly and time consuming. It is more cost effective to use a well polished master model and save on finishing of the many items of jewellery produced from it. Allowance must be made for the shrinkage on cooling of the casting and in the shrinkage of the rubber mould in the model dimensions.

Models, particularly silver models, should be rhodium plated to prevent sulphur, emitted by the mould rubber during vulcanising, from attacking the master model and degrading the rubber surface, thus spoiling the finish, and to impart a hard scratch-resistant surface. The master model may well be used several times over a period of time to make replacement rubber moulds. Sulphur attack is often evident as a blackening of the surface and the rubber mould may be more liable to crack.

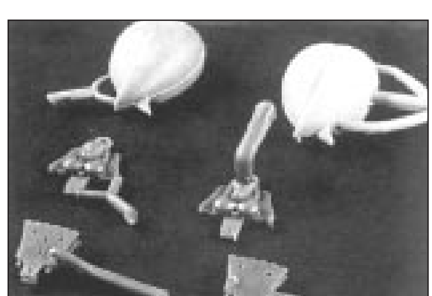

Figure 3 - Gating of wax patterns. (a) Left: as designed (b) Right: As modified for successful casting

The size of the gate, which is an integral part of the model, is another point to be carefully considered. In this regard, there are no mathematical rules. The gate must feed the liquid metal to the casting as easily as possible and should act as a liquid metal reservoir up to complete solidification, in order to compensate for the volume contraction. It should be circular to minimise the surface area and hence cooling rate; the gate should solidify *after* the casting to avoid shrinkage porosity. As a rule of thumb, keep the diameter of the gate at least equal to the section of the model it feeds into. Gate (or gates) size and position are very important. Tapering of the gate should be strictly avoided; it produces an obstruction and reduces strongly the gate performance. Where possible, it should be positioned to minimise its impact on finishing. Many incomplete fills or shrinkage problems are attributable to inadequate gating. Figure 3 shows some waxes of items with poorly designed gates (left side) and the items with redesigned gates (right side) necessary to get good castings.

In some cases, the master model is made of wax, either hand carved or, increasingly, produced via CAD and rapid prototyping technology.

Making the rubber mould

Good quality rubber moulds are essential for quality castings. There are many moulding rubbers available in the market made from natural and synthetic rubbers including the silicone rubbers. Each grade has different properties and is used in different situations, depending on requirements. Some are more durable, flexible and less likely to crack or distort the wax on removal; others may be harder and better reproduce highly polished surfaces, but may be less durable and more likely to crack. It is recommended to seek advice from the rubber supplier as to the preferred rubber grade to use for particular items. Cold setting silicones and liquid 'rubbers' that set at ambient temperature and do not require vulcanising at temperature are also available commercially and are suitable for making moulds from delicate temperature sensitive models or original artefacts.

Allowance must be made for shrinkage of some rubbers in the master model dimensions, although non-shrink rubbers are available. The use of silicone rubber is recommended as working is easier, there is good surface reproduction and the wax patterns are more easily extracted. However, they are prone to cracking and can hinder the escape of air during wax injection. The latter can be overcome by cutting vents in the mould. The moulds must be kept perfectly clean during use; foreign materials (e.g. talc powder and dust) give rise to surface defects on the wax patterns, which are later transferred onto the gold alloy castings.

The master model is placed between rubber sheets in a mould frame (forged aluminium), Figure 4, and then cured – or vulcanised – by subjecting them to a combination of pressure and heat in a heated press. There is an optimum temperature for curing (vulcanisation); For conventional rubbers, it is typically about 158°C within the widest acceptable range of 143-173°C. However, the optimum temperature depends on the rubber type and the rubber supplier's recommendations should be followed. The moulding frame containing the rubber mould is left in the press for some minutes before the heating cycle is started and pressure is gradually applied. The time at temperature depends on mould thickness, e.g. 30 minutes for 12mm thick; 45 mins for 18mm and 75 mins for 36mm (maximum recommended thickness for a rubber mould is 36mm). Remember, rubber is a poor conductor of heat and it takes time for the centre of the mould to attain the correct temperature. It is also important to calibrate the vulcanising press for temperature from time to time. Some presses have poor heating distribution and temperature regulation.

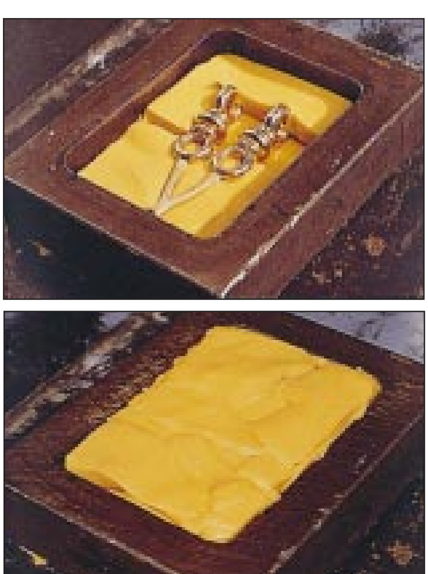

Figure 4 - Preparing the rubber mould

After vulcanisation, the rubber mould should be cut into 2 matching halves with a sharp scalpel along the main gate and have sharp undulations to assist precise registration between top and bottom halves of the mould during wax injection, Figure 5. It is important to avoid separation lines on the main surfaces of the waxes that will be produced from the rubber mould, as this will lead to extra finishing of the castings, and to avoid damaging the master model when cutting the mould. Cutting of the mould requires a high skill level from the mould-maker.

In cases where the master model has marked undercuts, such as a hollow ring of 'C' section, a more complex mould comprising 3 or more parts needs to cut after vulcanising. Cutting of such a rubber mould requires some experience to achieve a successful mould for investment casting.

It is possible to buy pre-cut mould rubbers that have registration pegs already included, Figure 6, or to include cubes of old vulcanised rubber to act as pegs during mould assembly, prior to vulcanising. Faccenda described such an approach at the Pomellato factory at the Santa Fe Symposium 1999 (3).

Figure 5 - Cutting the rubber mould

Figure 6 - Mould using prelocating pegs

Making the Wax Patterns

Multiple wax patterns are made by injecting molten wax into the rubber mould. It is important to use good quality waxes with a narrow melting range. Again, there are different grades available, each with different properties suited to particular situations. Some waxes are softer but more flexible, making removal from the mould less of a problem. Where a highly polished surface is required to be reproduced, then a hard mould rubber and a harder wax may be appropriate. If you experience problems, ask the wax supplier for advice on appropriate grades. It is unlikely that one grade of wax can meet all the needs in a casting facility, especially where there is a large range of casting shapes, types and sizes.

In some cases it is suggested that the wax used for the main central sprue is different from the one used for the wax patterns. The main sprue wax should melt at a lower temperature than the attached patterns, to avoid tensional stresses (and consequent cracking) in the investment during dewaxing.

The waxes should not leave carbonaceous residues after burnout from the investment mould, or flask as it is called; these residues can give rise to surface defects in castings including porosity. A simple way to test a wax for carbonaceous residues is to put a sample in a silica crucible and to submit it to the entire burnout cycle. If the crucible has black residues, this is carbon from the wax.

The hot molten wax is injected under pressure into the rubber mould from a wax injector, or wax pot as it is often called, Figure 7. A good wax pot should guarantee constant temperature and pressure. Modern vacuum injection units have autoclamp devices, which control volume and weight of the wax pattern produced for consistent mass production of patterns (or 'waxes' as we call them). Inconsistent wax weights, and hence casting weights, are a common problem due to inconsistent wax and clamping pressures. Clamping the mould between metal plates by hand can suffer from operator fatigue. One mould clamped and injected at a time please! The author has seen operators with "sandwiches" of 3 moulds, hand-held, being injected in a batch in the Far East, 1-2-3! Speedy but not recommended where quality and consistency is important.

In many instances, the mould will be lightly dusted with talc or sprayed with a mould release agent prior to wax injection to facilitate easy removal of the wax after setting, although there are many companies who only talc 'difficult' moulds, but not 'normal' ones. It is human nature to give moulds a 'good' dusting of talc rather than a light dusting; remember, the talc will get pressed into the wax pattern surface and degrade surface quality. The use of corn flour or maize starch is an alternative which will burn off during investment mould burn-out.

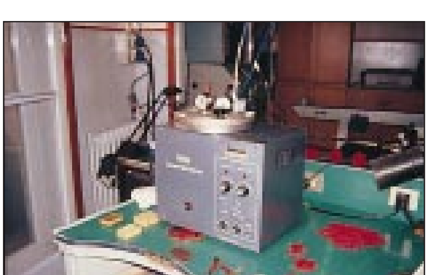

Figure 7 - Wax vacuum injector

It is important to clean the moulds of accumulated talc regularly or else the wax will not faithfully reproduce the required shape and the surface quality will be poorer. Lastly, it is important to store them, when not in use, in dust-free conditions out of strong light in a dark place such as a drawer or cupboard. Most rubbers deteriorate in sunlight. Each mould should be uniquely coded and the wax injection conditions noted for future use, for consistency of quality. They should be inspected regularly for signs of damage and deterioration and discarded, if necessary. It is a simple task to make a new replacement mould from the original master model. There is no point in using a damaged mould as it will lead to damaged waxes and cause additional work and cost in finishing the jewellery after casting.

The wax patterns should be carefully inspected before mounting them on the tree. Defective ones should be promptly discarded to avoid time wasting in the following manufacturing cycle. It is cheaper to discard them and make a new wax than to spend considerable time in repairing defects. It is all too common to see workers spending considerable time repairing defective waxes. In some wax shops, up to half the staff are involved in this task. It is not cost effective!

Never recycle old, defective waxes if you want quality castings, although it is permissible to recycle clean wax in the central sprue, as it will have little impact on casting quality. Certainly, never recycle old wax from dewaxing! Wax degrades on melting over time and can also pick up dust and investment particles.

Also, it is not recommended that waxes are made and stored over long periods before use. It is better to make fresh batches. When made, store carefully in trays under cool conditions before assembling on the tree; do not heap them in a jumble, as they are liable to damage and distortion. Keep unused waxes clean from dust by covering or place in a drawer.

The position and size of gates on wax patterns are important; they influence metal flow, direction of solidification and the possible incidence of shrinkage porosity, as discussed in the previous section. Round gates please, not square section or tapered, if you want to avoid shrinkage, incomplete filling and other problems.

Assembling the Wax Tree

As far as possible, assembling patterns that have very different shape, size and weight on the same tree should be avoided. If this is not possible, have the smallest patterns at the top and the largest at the bottom end (where the feeder button is situated). Moreover, the wax patterns should not be put too close together, to avoid dangerously high temperatures in the investment, when the metal is poured. Remember, this space will become the investment mould wall. If it is too thin, it will get very hot and can lead to gas porosity and poor surface quality in the castings.

Ideally, the central sprue should be tapered, being thicker at the bottom end. Traditionally, the waxes are mounted at an angle of 30-45° to the horizontal (tree vertical). This is optimum for centrifugal casting. Where static vacuum casting equipment is in use, modern thinking is that wax patterns should be attached to the sprue at a lower angle, 10-20° to the horizontal, to assist in controlling the direction of solidification, when casting, from the outside of the tree in towards the central sprue. This will help to prevent shrinkage porosity.

Waxes should be mounted in a spiral up the central sprue, Figure 8, not in straight vertical lines, as this can adversely affect the pattern of solidification. Cluster mounting of small items is useful. For small numbers of parts, a horizontal platform arrangement can be used, Figure 9.

The welding spots, which attach the patterns to the main sprue, must be well rounded, smooth with no undercuts as this would give a narrowing of the gates in the mould, Figure 10. Narrowing can impede molten metal flow into the casting and can give rise to non-metallic inclusions, from investment that breaks off at the undercut, when the liquid metal is poured.

Also ensure that the wax sprue flows smoothly into the rubber base to provide a smooth cone (sprue button) without any ledges that can give rise to turbulence on pouring the molten metal.

Remember to weigh the whole wax tree, to allow calculation of the weight of precious alloy needed for casting. Rubber bases should be weighed separately and coded so that the weight of wax can be calculated. The weight of the wax tree (less base) is multiplied by the alloy density to calculate the gold alloy weight required for casting. This is a good ‘rule of thumb’, although adjustments may need to be made based on actual experience. Thus, it is important that the densities of all gold alloys to be cast are known. If your supplier cannot give you these values, determine them using Archimedes principle on a weighing balance.

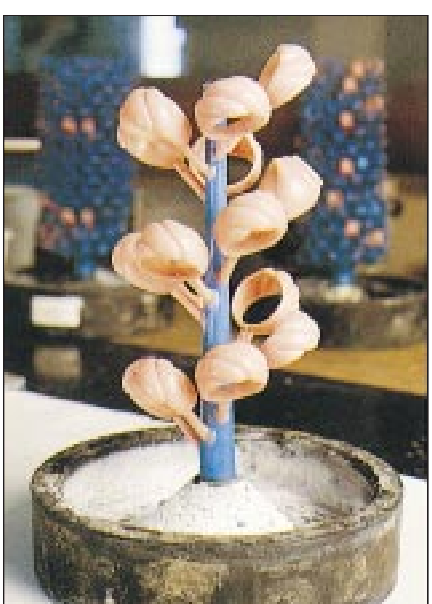

Figure 8 - Mounting waxes in a spiral on tree

Figure 9 - Platform mounting of waxes on sprue

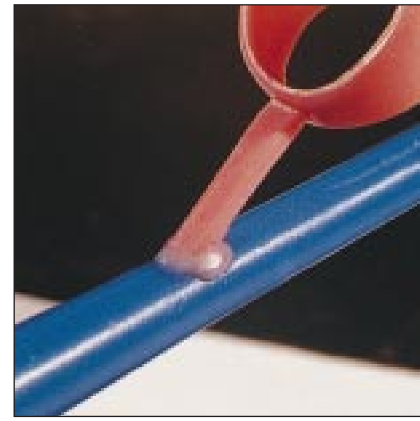

Figure 10 - Smooth fillet on wax join to sprue

The assembly of the wax tree can be done horizontally or at an angle in a special jig or vertically, whichever is more comfortable for the tree assembler. A number of jigs are available on the market but many casters make their own. Some casters prefer to use hollow central sprues as they can enable more waxes to be assembled on the tree but with less feeder metal than a solid sprue of the same diameter. This means less feeder to be recycled in subsequent melts.

Wax trees are prone to dust pick-up due to static electricity; if this is a problem, then the tree can be dipped in a proprietary commercial surfactant or dilute detergent solution, rinsed in deionised water and dried.

Concluding remarks to Part 1

This paper has concentrated on best practice of the first 4 stages (excluding design) of the investment casting process. The importance of doing them correctly cannot be over-emphasised if good quality castings are desired. It should also be emphasised that making moulds and waxes and assembling the wax trees should be carried out in clean, dust-free conditions in an area separate from the area for investing the plaster mould, burn-out and casting.

For more detail and understanding of these processes and the underpinning technology, the reader is recommended to read the many relevent articles in earlier issues of *Gold Technology* and in the WGC technical publications listed under References below.

The concluding Part 2 of this article covers the investing of the wax tree to produce a mould through to successful casting and will be published in a future edition of *Gold Technology*.

References

1 Solidification of gold alloys: see articles by Mark Grimwade in *Gold Technology* No 2, June 1990.

2 See section 3 in 'Handbook on Casting and Other Defects', Dieter Ott, 1997, pub. WGC, London

3 "Quality level improvement in investment casting...", V.Faccenda, Proc. Santa Fe Symposium, 1999, p.271

Recommended for further reading:
Gold Technology, No 7, 1992, No 11, 1993, No 13, 1994, No 17, 1995, No 20, 1996 and No 23, 1998. These all cover aspects of investment casting.
Investment Casting Manual, World Gold Council, 1995.
Handbook on Casting and Other Defects, World Gold Council, 1997.

All back issues of *Gold Technology* and WGC technical publications are available from World Gold Council, International Technology, 45 Pall Mall, London SW1Y 5JG, U.K.

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