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Metal Casting: Back to Future

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ABSTRACT

Future requirements of castings – thin intricate shape, minimal machining and small order quantity – can be met by going back to the time tested lost wax casting process. It was perfected in India over many centuries, but started getting ignored in the last few decades owing to other processes for mass production developed in the West, many of them with unacceptable environmental effects. In this paper, we take a comprehensive look at the ancient art of investment casting, its current state-of-the-art and some emerging computer-aided technologies relevant to wax pattern development. A hybrid methodology is proposed combining the strengths of all three (capabilities inherited from the past, resources available at present and appropriate technologies borrowed from the future), and validated by a real-life experiment. We hope this will motivate Indian foundries to critically assess their capabilities, and explore new combinations of metal, process, geometry and application to establish a niche in the global market.

Keywords: Ancient India, Casting, CAD/CAM, Investment Casting, Lost Wax Method, Net Shape Manufacturing, Pattern and Mould.

1. INTRODUCTION

It is well recognized that casting requirements have significantly changed in the last few years, owing to technology push (mainly CAD/CAE/CAM and miniaturization) as well as market pull factors (such as better appearance and competitive cost). Future castings will be smaller, more intricate with freeform curves and thin walls, and will be required in net shape (zero or just finish machining). The order size will further reduce owing to shorter product life-cycles, continuous design improvements, lower inventory requirement and mass customisation, leading to *single-casting-on-demand* systems.

The current most widely used processes, including sand casting and die casting, cannot fully meet the above requirements. Sand casting cannot produce thin walls and has environmental concerns; diecasting is suitable only for non-ferrous metals and for large order quantities; and both have cost magnification when multiple intricate undercuts are present. Interestingly, although these and many of the newer casting processes were developed in the West, they no longer find favour there, and the castings are being procured from developing countries.

Although India has a long tradition of metal casting, has the world's largest pool of engineers, is blessed with rich deposits of major metals, has a large local market itself, and has made giant strides in information technology (especially in providing IT services to other countries), it has not blended these resources to establish manufacturing supremacy. Indian foundries produce barely 4% of the global output of castings and have an even lesser share of the export market at present.

Interestingly, one of the ancient and time-tested processes: the lost wax or *cire perdue* (*cire*=wax, *perdue*=lost) casting method, can meet the requirements mentioned above. Although the earliest lost wax castings were produced more than 5000 years back in India, the process was reinvented in 1940's in the West and renamed as investment casting. It was initially used by jewellery and dentist workers, but took off rapidly when applied to industrial castings such as aircraft and armament parts. Modern investment casting process can give the highest dimensional tolerance (1 micron per mm), best surface finish (1-2 micron) and thinnest sections (about 1.5 mm) compared to other casting processes with the exception of pressure diecasting. Moreover, undercuts can be produced without using cores, draft is usually unnecessary and flash is absent. There is no limitation on the type of metal to be cast, and the process is especially suitable for small parts weighing less than 20 kg, though larger parts up to 100 kg are regularly produced. Thus investment casting stands out in comparison to other processes in meeting the emerging requirements mentioned above.

There is another strong reason: India is well known worldwide for its investment casting skills, especially through the '*Chola bronze*' and '*Dhokra iron*' art castings that are produced even today by thousands of artisans spread all over the country. This process therefore deserves renewed attention from the foundry community. Perhaps a hybrid methodology derived from ancient investment casting, but adapted to industrial requirements through appropriate, economical and nature-friendly technologies, may be well suited to India. To explore this premise further, let us first briefly study the ancient methodology, the current state-of-art, and some future technologies relevant to investment casting.

2. ANCIENT LOST WAX PROCESS

Metal casting has been mentioned in ancient Sanskrit texts such as *Shilpashastra* and *Yantra Sarvasva* and detailed in mediaeval texts such as *Shilparatna* and *Manasara*. The major application was in creating the idols used for worship; and very strict rules were laid down to achieve perfection in terms of *talmana* (proportions), *mudra* (stance) and *bhava* (expression). Other products included lamps, doors, frames, bells, cooking utensils, agricultural implements and weapons.

Earliest evidence of castings was found in the excavations of Indus Valley (3000-4000 BC) including the 11 cm high bronze dancing girl, cast ornaments, figurines and other items of copper, gold, silver and lead, besides kilns for smelting copper ingots and casting tools. The earliest iron castings emerged in India around 2000 BC, and its use in pillars, arrows, hooks, nails, bowls, daggers, etc. is confirmed by excavations in Delhi, Roopar, Nashik and many other places. Large scale state-owned mints and jewellery units have been mentioned in Kautilya's *Arthashastra* (about 500 BC), including the processes of metal extraction and alloying. The *Ras Ratnakar* written by Nagarjuna in 50 BC mentions the distillation of zinc and its casting, proved through recent excavations in Zawar, Rajasthan. The *Nataraja* and *Vishnu* statues of Chola dynasty (900-1200 AD) stand testimony to the fine practice of intricate castings in mediaeval India. Most of these were made in *Pancha Dhatu* – usually an alloy of copper, zinc, tin (or lead), gold and silver, using the *Madhuchista Vidhana* or lost wax casting process.

The ancient lost wax process is still practiced in many districts all over India, such as in Bankura (West Bengal), Mayurbhanj, Puri and Cuttack (Orissa), Tirupathi (AP), Thanjavur and Salem (Tamil Nadu), Mannar (Kerala), Mysore, Gulbarga and Belgaum (Karnataka), Kolhapur and Nashik (Maharashtra), Bastar (Chattisgarh), Aligarh and Moradabad (UP) and Mandi (HP). Similar practice is also found in Nepal, Thailand and beyond. Some of the clusters have more than a hundred units, such as in Swamimalai in Thanjavur district.

Fig. 1. Ancient lost wax casting method: wax model sculpting, clay covering, wire clasped mould for dewaxing, as-cast Ganesha, and finishing

The most difficult and time-taking step in the entire process (see Figure 1) is the sculpting of wax patterns; a medium-size idol pattern can take 4 weeks or more. A mixture of bees wax and *vriksa rasa* (natural resin obtained from specific trees) along with a little cooking oil (mustard, ground nut or coconut) is prepared, heated well and poured into sheets, to facilitate cutting and adding to the models. Each model is unique. In some cases, when multiple (ten or more) orders for the same model are placed, then a plaster or cement mould is made for making a rough shape of the wax models before detailed carving using spatula, knife and scraper, etc. The carved wax model is carefully pasted over (except for one or two holes for wax removal and metal pouring) with initial layers of fine river clay (or alumina sand plus bentonite), followed by coarser clay. Small amounts of charcoal, gingillee oil, cowdung and natural (tree) resin may be added to the clay, especially for cores.

The clay-covered models are dried in the sun for 2-4 weeks until they are hard enough for handling. Then they are tied with metal wire (to prevent expansion and breakage during dewaxing), and heated using cow dung cakes for melting out the wax, which is collected for reuse. An alloy of copper (84%), zinc (14%) and tin (2%) is used for making a '*Chola Bronze*' statue. For idols to be used in worship, small amounts of gold and silver are also added. Iron and lead may be added for other applications. The metal charge is calculated in terms of the weight of the wax model (usually 8-9 times) and melted in a crucible furnace using wood charcoal and coal as fuel. Hand-operated bellows are used for blowing air into the furnace. The mould is preheated to the metal temperature before pouring. After cooling, the mould is broken to reveal the casting. The gates and risers are removed, followed by filing and polishing to obtain a brilliant shine. Finer features are obtained by chiselling with iron nails.

Thus the ancient investment casting was characterized by natural materials and energy resources, and low-cost devices, leading to its proliferation in almost all parts of the country. However, manual crafting of the wax patterns requires considerable skill honed over many years, usually passed on from generation to generation and confined to specific families. There is another major limitation: each pattern can be used for making only a single casting.

3. CURRENT INVESTMENT CASTING

The industrial investment casting process is meant for producing medium order quantities, and hence the expendable patterns are produced by injecting wax in a die made of aluminium or steel. Die design and manufacture determines the complexity and accuracy of the pattern and hence the casting. It requires a parting (leading to flash), draft (though minimal) and sometimes cores (for holes and undercuts). But it is possible to make a wax pattern in pieces and join them together, followed by some finishing (removal of flash, etc.), thus providing additional freedom to produce complex castings. Further, cores can be placed to produce hollow castings.

The expendable pattern material is usually petroleum-based paraffin wax with some blends (like polymers and resins), mainly for higher dimensional stability and strength. It is recyclable (can be used for feeders and gating system) and environment-friendly. It is injected into the die at around 50 C under a pressure of 5-25 kg/cm^2 depending on part size and section thickness. The wax patterns are removed from the die, hand finished to remove flash and welded using a simple gas flame torch around a sprue to form a cluster or tree. The tree is dipped into agitated slurry of fine refractory material (typically zircon sand) and binder immediately followed by stuccoing or showering with dry sand. The shell is left to dry for 6-12 hours in an air-conditioned room. The process is repeated 10-15 times to finally produce a ceramic shell 6-10 mm thick (see Figure 2). Initial layers are built with fine sand, to obtain good surface finish, whereas subsequent layers are built with coarse sand, to obtain high permeability.

Fig. 2.Industrial investment casting process: wax injection pattern, attaching to gating, dipping in ceramic slurry, sand stuccoing, controlled drying and pouring in hot mould.

The wax is removed from the shell by heating it to about 120 C in a pressurized steam autoclave to prevent shell cracking, followed by heating to about 1000 C to vaporize any residual wax, impart strength to the shell and make it ready for receiving the metal. The metal is melted (usually in an induction furnace) and poured into the red hot shell removed from the furnace. After casting solidification, the shells are broken, followed by fettling and shot blasting. Final finishing and heat treatment may be performed, if necessary.

The process requires technical expertise and shop-floor discipline. Several technological improvements have been made in the last few years, such as wax additives to improve its fluidity and strength, the use of fibre materials to improve the strength of ceramic shells, new core materials (ex. water solvable), vacuum assisted counter gravity casting to improve mould filling, and advanced applications such as medical prosthetics and turbine blades with long columnar grains.

In summary, the modern investment casting process can produce net shape parts (requiring zero or no machining) in low to medium order quantities with moderate investment in equipment and facilities. The major limitation of the ancient process, that is manual crafting of wax patterns, is overcome by automating their production. However, a new bottleneck is introduced: the design and manufacture of the wax injection die, which requires considerable technical expertise and time, and can be justified only if the order quantity is sufficiently large.

4. FUTURE TECHNOLOGIES

Here we highlight some of the latest computer-aided technologies (see Figure 3) that can automate or substantially speed up the task of pattern development for one-off castings, as well as die development for multiple castings. The applications are meant for castings with intricate shape and the backbone is a 3D model of the casting. We will focus on: (1) creating a solid model of an existing or new casting, (2) 'intelligent' methoding (design of feeders and gating), and (3) automatic fabrication of the wax pattern by rapid prototyping systems. Dies can also be manufactured using rapid prototyping based routes.

4.1 Solid Modelling of Intricate Shapes

While CAD/CAM technology is well established for machined components, it is not as widely used in the foundry industry. This is mainly due to the difficulty in modelling castings, especially those with free-form surfaces and intricate features. The user inputs for even high-end or 'friendly' solid modelling systems (such as CATIA, Pro-Engineer, SolidWorks and Unigraphics) is primarily through a digital mouse moving on a 2D plane. This is inadequate to define the 3D shape of complex castings. It is not surprising that it takes 4 weeks or more to create the solid model of a 6-cylinder engine block or an intricate sculpture.

There are two futuristic technologies that overcome the above limitation. The first one eliminates solid modelling altogether, but requires an already existing physical model. It involves 3D scanning of the model surface by a laser beam system (such as Laser Design, www.laserdesign.com), which generates a 'cloud of points'. The cloud is taken into a 'Reverse Engineering' program (such as Raindrop GeoMagic, www.geomagic.com) to fit surfaces through the points and stitch the surfaces together to finally convert into a solid model that can be imported into any 3D CAD system.

Fig. 2. Some modern technologies relevant to investment casting of complex parts.
Left- touch based solid modelling; right top- intelligent feeder design and analysis;
right bottom- rapid prototyped wax model and corresponding rubber mould.

The second solution is to use a haptic or touch-based solid modelling system, such as FreeForm pioneered by Sensable, USA (www.sensable.com). The system includes a robotic arm called Phantom (originally developed in MIT, USA). This can be gripped by the user and moved in real 3D space to sculpt virtual clay – much as an artisan sculpts a real clay model – using different types of tools (ball, knife, etc.). The arm provides force feedback to the user, allowing him/her to feel the resistance of the material based on its hardness, thickness and the type of tool. Immediate visual feedback is provided on the display monitor, enabling eye-hand co-ordination. The virtual clay can be added, pushed, pulled, rounded, cut and mirrored, enabling quick modelling of even complex shaped art castings.

4.2 Intelligent Methoding and Optimisation

Once a solid model of the casting is available, it is possible to design the methoding (essentially, mould layout, feeders and gating system) in a virtual 3D environment, followed by casting simulation to predict internal defects such as shrinkage porosity and inclusions. Based on the results, the user can modify the methoding and verify it again by simulation. Several casting simulation programs are available today and quite well established: Magma (www.magmasoft.com), Pamcast/Procast (www.esi-group.com), Novasolid/Novaflow (www.novacast.se), Solidcast (www.finitesolutions.com) and a few others. They are however, rarely used by the large number of small and medium size foundries, owing to the high cost of the software and support involved, and difficulty in attracting and retaining the technical manpower required to run the programs.

An intelligent methoding program AutoCAST developed by the first author and Advanced Reasoning Technologies (www.adva-reason.com) uses geometric reasoning algorithms to automatically suggest methoding solutions (ex. feeder location and its starting size), automatically model the feeders/gates and accurately predict casting defects such as shrinkage porosity. This enables a methoding engineer to design, model and analyse a layout of even complex castings within an hour. Thus several iterations can be completed in a single day, to find the most optimal methoding solution that gives defect-free castings with the highest possible yield. The user interface is specially designed so that even a senior foundry engineer without any prior exposure to computers can learn to operate the program in a single day. This eventually paves the way for widespread use of even advanced simulation such as microstructure and residual stress, that require not only a good background in metal casting but also in Finite Element theory and its application to fluid flow, heat transfer and stress analysis.

4.3 Rapid Prototyping of Casting Patterns

The rapid prototyping technologies developed over the last decade enable automatic fabrication of a physical model directly from its 3D CAD data without any part-specific tooling. A special software slices the CAD model into a stack of cross-sections and sends these to an RP machine. The machine builds the sections one on top of another from bottom up. In the last few years there have been rapid developments in the accuracy, surface finish and build speed of RP parts. At present, there are over 30 companies world wide offering a variety of RP machines based on different materials and techniques for building and binding the layers (www.wohlersassociates.com)

Patterns suitable for investment casting can be built using RP systems such as Fused Deposition Modeling (www.stratasys.com), Stereolithography and Thermojet (www.3DSystems.com), ZPrinter (www.zcorp.com) and Layered Object Manufacturing (www.helisys.com). In liquid-based systems, the portions of the part lying above any undercuts are supported on independent structures created along with the part (using a different material as in FDM, or the same material as in Stereolithography). The support structures need to be manually removed after the fabrication is complete, which is a difficult and time-consuming task, especially for intricate shapes. Even in LOM patterns the removal of excess paper outside the cross-section boundary (which acts as the support) is somewhat difficult for intricate shapes. This difficulty is eliminated in powder-based systems (Thermojet and Zprinter), since loose powder provides the support in undercut regions and can be simply shaken off after fabrication is complete.

The patterns built by the RP processes mentioned above are made of materials different from the industrial wax used in investment casting, and the process may require some experimentation and adjustment to use the RP patterns. For example, the Stereolithography and LOM patterns leave an undesirable ash residue during burnout. The RP machines and materials are still quite expensive, and therefore suitable only for one-off parts, especially small and intricate ones. If a larger number of wax patterns are required, then a silicone rubber or polyurethane mould (see Figure 3) can be prepared for injecting the wax. The master pattern required for 'casting' the mould can be built in an RP machine using a harder material such as ABS or epoxy. It is also possible to make a metal mould for injecting the wax using a direct RP route such as Selective Laser Sintering (www.eos-gmbh.de) or an indirect route such as making a wax RP model of the mould halves followed by investment casting. A separate investigation is underway to study the techno-economic feasibility of various routes.

5. HYBRID APPROACH AND CASE STUDY

To fulfil the emerging requirements of castings as mentioned in the beginning, we need a process that has the following characteristics:

(1) Suitable for one-off castings or small order quantities,
(2) Minimum steps and time to finished product (compared to other routes),
(3) Automated or easily controllable (to achieve quality consistency and reliability).

These can be fulfilled by combining the strengths of the ancient, current and futuristic methods and evolve a hybrid approach that will comprise the following steps:

(1) Part solid modelling: using a reverse engineering system for existing castings, or a 3D modelling system for new castings.
(2) Optimal methoding: using an intelligent program for feeder and gating design, followed by simulation for ensuring defect-free castings.
(3) Tooling fabrication: wax pattern for one-off castings by direct rapid prototyping, or wax injection die by either direct or indirect routes based on rapid prototyping.
(4) Shell/mould making: ceramic shell for small, thin walled castings requiring high geometric fidelity, or clay mould for larger, thicker walled castings requiring moderate geometric fidelity.
(5) Dewaxing, pouring and fettling: using appropriate equipment and methodology currently practised in the industry.

To validate the proposed hybrid approach for an intricate casting, we chose *Ganesha*, the Lord of knowledge and remover of obstacles, whose vehicle is a mouse. An ancient drawing of *Ganesha* was taken from an *Agama* from Saraswathy Mahal Library, Thanjavur (see Figure 4). The drawing, comprising of the front and side views, was scanned and imported into the haptic-based solid modelling system as a reference. Then by adding and shaping digital clay, the shape of *Ganesha* was gradually developed. It took about 25 hours over 5 days to complete the solid model, significantly less than the time that would have been taken by a conventional solid modeller.

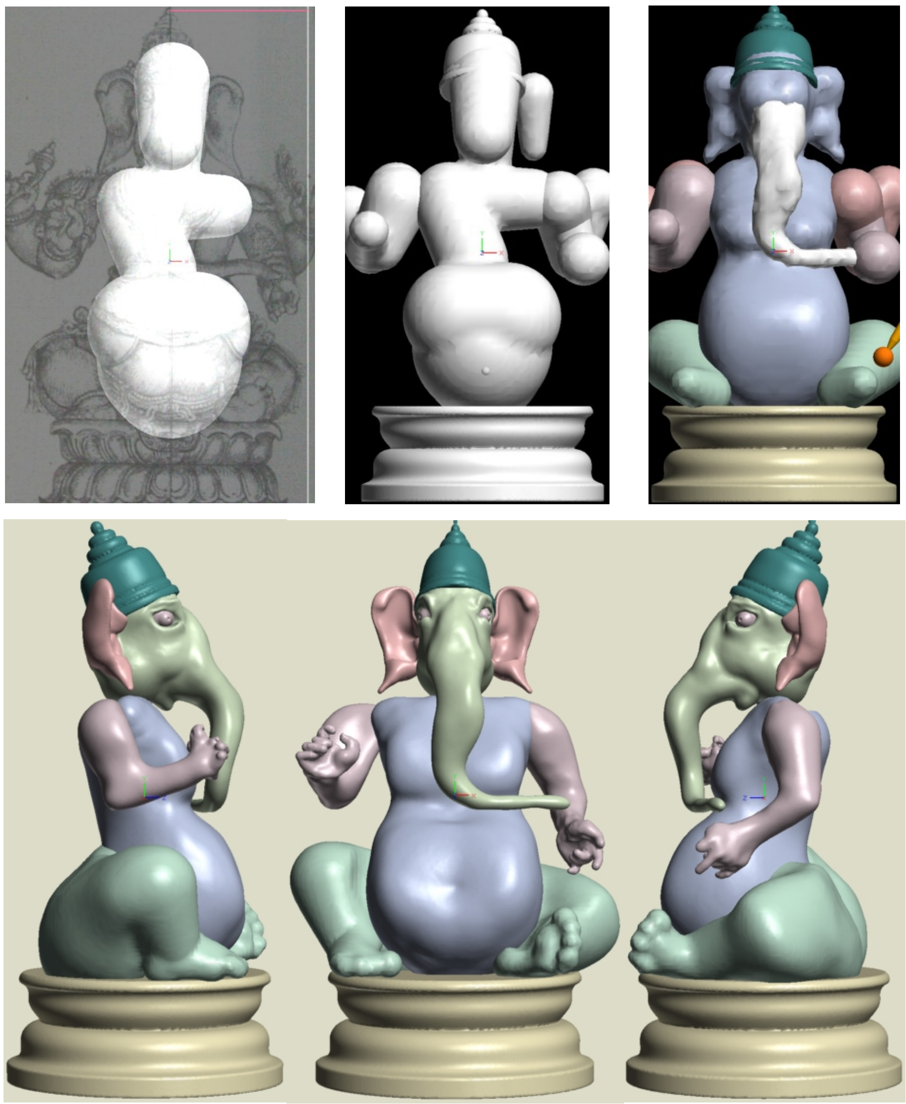

Fig. 4 Creating a Ganesha model using a touch-based system.
Top- registering the drawing, adding virtual clay and shaping;
Bottom- front and side views of the final model.

The solid model was then converted into an STL file with about 200,000 facets. This was imported into the casting design software for methoding and casting simulation. The digital model was sent to the Rapid Prototyping Lab at GTRE, Bangalore for wax pattern fabrication on a Thermojet RP system. This took about 12 hours. The wax pattern was then taken to Uni Deritend Ltd., Thane for investment casting. After removing the support structures the ceramic shell was created over the next four days, after which austenitic stainless steel was poured into the hot shell to obtain the Ganesha (see Figure 5).

Fig. 5 Physical realisation of Ganesha: wax pattern made by rapid prototyping, followed by support structure removal and investment casting.

6. CONCLUSION

India has proven capability in the ancient art of metal casting as well as the latest information technologies, but needs to combine these capabilities to surge ahead in the global race of competitive manufacturing. As shown in this paper, the emerging requirements of castings (intricate, near-net, casting-on-demand) can be met by a judicious combination of appropriate technologies borrowed from the past, present and future. One such proposed route is through computer-aided design and rapid prototyping technologies for pattern development, followed by clay-moulded (ancient) or ceramic shell (current) methods for investment casting. The hybrid route may be currently economically justifiable only for one-off intricate castings required urgently. This includes replacement parts for critical equipment (such as in defence) and medical prosthetics (crano-facial, hip, femur and knee bones for victims of accident, cancer and deformities). However, with reducing costs of the systems involved and improving efficiency of the processes, we strongly feel that the approach will gradually expand its reach. It is important for the foundries to experiment with such new routes, identify the best combination of application, geometry, material and process, and specialise in that combination to establish a niche in the global market.

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