Investment Casting Development:
Ancient and Modern Approaches

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Abstract

The ancient art of bronze castings involved painstaking sculpturing of individual wax patterns, followed by clay covering, sun drying, dewaxing, metal pouring and manual finishing, taking several months for each casting. It required a high degree of aesthetic sensitivity and artistic skills honed over decades under the tutelage of senior craftsmen. This art is still practiced in several pockets of India and its products are in growing demand, especially from overseas customers. On the other hand, industrial castings require consistent quality (conformance to customer or design specifications), ever shortening lead-time to delivery and competitive costs, making it imperative to introduce computer-aids in casting development. This paper presents both scenarios: ancient and intelligent, with real-life examples taken from the industry. We conclude by observing that both sectors can learn from each other, improving the overall customer satisfaction.

Ancient Art of Casting

India has been well known for its metallurgy and castings over several millennia. These are mentioned in several Sanskrit works such as Shilpashastra and Yantra Sarvasva derived from Sthapatyaveda containing the principles of realizing all kinds of man-made structures, in turn derived from Atharvaveda, one of the four principal Vedas. The original authors are said to be Viswakarma and Maya, the ‘chief engineers’ of gods and demons, respectively. The Rigveda mentions equipment used in casting, such as dhamatri (cupola), gharma arammaya (crucible) and bhashtri (blower). 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). In particular, dhyana slokas define the spiritual quality of each deity and the lakshanas describe the form. Other products included lamps, doors, frames, cooking and agricultural implements.

Earliest castings include the 11 cm high bronze dancing girl found at Mohen-jo-daro (around 3000 BC). The remains of the Harappan civilization contain kilns for smelting copper ingots and casting tools. The castings were made by pouring bronze in sand or stone molds. Cast ornaments, figurines and other items of copper, gold, silver and lead have also been found in Indus valley excavations. Iron has been mentioned in the Vedas as ayas, and iron pillars, arrows, hooks, nails, bowls, daggers, etc. were made as early as 2000 BC, confirmed by excavations in Delhi, Roopar, Nashik and many other places.
Large scale state-owned mints and jewelry units have been mentioned in Kautilya’s *Arthashastra* (about 500 BC), including the processes of metal extraction and alloying. Later Sanskrit texts talk about assessing and achieving metal purity. The *Ras Ratnakar* written by Nagarjuna in 50 BC mentions the distillation of Zinc in Zawar, Rajasthan, which has been proved through recent excavations.

The 5th century Iron Pillar of Delhi, which stands 23 feet, weighs 6 tonnes and contains 99.72% iron without showing any signs of rust, is a remarkable example of the level of metallurgical science in ancient India. The *Nataraja* and *Vishnu* statues of Chola dynasty (9th century) stand testimony to the fine practice of intricate castings in mediaeval India. Most of these were made in *Pancha Dhatu* (copper, zinc, tin, gold and silver) using the Madhuchista Vidhana (*cire perdue* or *lost wax*) process, described in detail in mediaeval Sanskrit texts such as *Silparatna* and *Manasara*. The Indian metallurgical science and casting technology was transferred to Europe through Portuguese explorers in 14th century, where it blossomed as a fine art. Vannocio Biringuccio, head of Papal Foundry in Rome (about 1400 AD) has been quoted as saying: “The art of casting… is closely related to sculpture,… it is highly esteemed… it is a profitable and skillful art and in large part delightful.” Indeed, the bronze sculptures represent the craftsman’s artistry as well as the capability of the casting process.

The ancient art of bronze casting is preserved to this date in several pockets of India. The most well-known and moderately flourishing cluster is in Swamimalai, located in central Tamilnadu between Thanjavur and Kumbakonam, less than 10 km from the Cauvery river. Here more than 200 units are continuously engaged in making the bronze castings. To study the process first hand, the author recently visited one of the units headed by Shri Rajan, and a brief account follows (see Figure 1).

The process starts with sculpturing the wax models by *sthapaties* (artisans), claimed to hail from the clan of *Viswakarma*. The wax is primarily bees wax, to which *vriksha rasa* (natural resin obtained from specific trees) and a little cooking oil is added. The mixture is heated 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 cement mold is made for making a rough shape of the wax models. The carving of each wax model takes 1-4 weeks depending on the size and intricacy. The rules laid down in *shilpa shastras* and *agamas*, which specify the proportions for various limbs of a sculpture, are strictly followed. Inspiration comes from the large number of ancient temples in this region, including the huge temple complexes of *Ranganathaswamy* in Srirangam, *Brihadeeshwara* in Thanjavur, *Thayagaraja* in Thiruvarur, and *Nataraja* in Chidambaram – all less than 100 km from Swamimalai. These were constructed by Chola kings between 900-1200 AD, though the main deities are said to be much more ancient.

After carving is complete, the wax model is carefully pasted over and covered with clay obtained from the riverbank (no additives are needed). Indeed, one of the reasons for the proliferation of casting units in this region is the suitability of clay from Cauvery. While most castings are made solid, some are made hollow using cores. The core sand includes additives like charcoal, gingillee oil, cowdung and natural (tree) resin. The first few layers are dried in shade and then the clay-covered models are placed in the sun to dry for 3-4 weeks. After this, the clay molds are tied with metal wire (to prevent expansion and breakage during dewaxing). For dewaxing, cow dung cakes are used as fuel, and the liquid wax comes out from a hole created for this purpose. For making decorative
castings, an alloy of copper (84%), zinc (14%) and tin (2%) is used. If the sculpture is to be used for worship, then small amounts of gold and silver are also added (making it a *pancha dhatu*); their percentages depending on the cost to be borne by the customer. In other parts of the country, different metals and compositions are used; other metals include iron, lead and mercury (making it an *ashta dhatu*). The metal is melted in a crucible furnace using wood charcoal and coal as fuel. Hand-operated bellows are used to blow air into the burning furnace. The mold is preheated to the metal temperature before pouring.

After cooling, the mold is broken to reveal the casting. The gates and risers are removed, and then the painstaking job of chiseling, filing, finishing and polishing starts. This takes 4-10 weeks depending on the size and details. At Rajan Industries, about 8-10 artisans are continuously engaged in this work alone. The large labour component reflects in the final cost; thus a 7 kg bronze statue measuring 15 inches may cost over Rs.4000. The main buyers are temples, offices and hotels, besides a growing export market. Today, these units are facing competition from diecasting units (for example, those in Faridabad, UP), which can produce bronze castings at less than half the cost of manually finished castings. The difference is however, clearly discernible: manual finishing gives a better shine, and makes it possible to produce many small undercut features, which is not possible in diecasting. The uniqueness of manually sculptured castings also adds to their value, especially in the export market.

**Computer-Aided Approach**

The modern approach to investment casting development is a result of two major factors. The first is the customer demand in terms of quality consistency (mainly conformance to geometry and property specifications), shorter lead-time (for sample part as well as regular production) and continuous reduction in cost (essentially tooling development and manufacturing costs, since material costs are usually fixed). These cannot be satisfied by conventional approaches alone. The second major factor is the decreasing availability of technically skilled and experienced manpower for processes that have a large number of human-controlled parameters, and therefore involve many changes in tooling and process parameters before producing satisfactory parts. Casting in general, and investment casting in particular, fall in this category, and require at least a decade of dedicated learning through trial and error or preferably under the able guidance of a senior engineer. With a sharp reduction in the number of qualified engineers taking up long-term careers in manufacturing, there is a serious problem indeed, and therefore industries are turning towards modern technologies to capture the domain knowledge and automate the processes.

Here we describe a computer-based approach to rapidly develop an investment casting, focusing on pattern design and methoding optimization, which is the most critical and time-consuming activity (see Figure 2).

The first step in computer-aided approach to casting development is the creation of a solid model using a 3D CAD software (like Pro-Engineer, SolidWorks or Unigraphics). These provide functions such as extrusion, revolution and Boolean operations starting from a 2D sketch or standard primitives (cube, cylinder, sphere, etc.), followed by modifiers (like draft and fillets). However, when intricate freeform shapes are involved (such as in art castings) the conventional CAD systems are inadequate. One answer is in haptic or touch-
based modeling systems (such as the Phantom from Sensable Technologies, USA), which literally allow a user to sculpt by holding a robotic arm and thus create a complex model in virtual space. The second approach, suitable when a physical model already exists, is to reverse engineer the solid model using one of the contact or non-contact systems. The systems give a cloud of points, over which a surface can be fitted and then converted into a solid model.

Using specialized modules in the CAD software (such as Pro/Casting) or specialized software (such as Delcam DUCT), the part model is converted to pattern model by applying draft, shrinkage, machining and other allowances. The parting plane may be identified interactively by the user by specifying the points along the parting line, or assisted by the software. Application of allowances is at best a semi-automatic task and at worst an interactive task (for example, the user identifying each face to which draft has to be applied and specifying the appropriate draft angle).

The next step is to decide the best design and layout of feeders and gating system. The feeder design involves identifying the last solidifying region (hot spot) inside the casting and placing a top or side feeder with appropriate shape and dimensions. The modulus principle may be used for the first approximation, but it has to be verified and optimized by casting solidification simulation. The simulation involves dividing the casting model into a number of cells (their size depending on the wall thickness and contoured surfaces), specifying the boundary conditions (such as metal to mold heat transfer coefficient at different locations along the interface) and displaying the results of analysis as color-coded maps of progressive solidification or directional solidification. If the casting is found to contain shrinkage porosity of size above the desired quality level, then the feeder design is improved (by increasing the size or number of feeders, or applying feedaids) and the simulation is repeated to verify the new layout.

In a similar manner, the gating can be designed to fill the mold in a specific time (too fast or too slow being undesirable). This is achieved by deciding the ideal filling time (based on metal, weight, section thickness and pouring temperature), and then calculating the choke area based on the velocity (obtained from the metallostatic head). Again, the gating design has to be verified by mold filling simulation, which can predict defects such as inclusions and cold shuts.

For best results, coupled simulation of mold filling and solidification simulation must be carried out, important for thin walled castings. Finite Element Method (FEM) based software are better suited than Finite Difference Method (FDM) based software, since the former can better approximate the shape of intricate and thin-walled investment castings.

After finalizing the pattern and methoding, the solid model of the individual or gated pattern can be transferred to a rapid prototyping station. Here, a wax replica of the virtual model is created layer-by-layer in wax or other materials suitable for investment casting. This includes Fused Deposition Modeling, Stereolithography QuickCast and Thermojet processes. The wax models produced by these can be used in the conventional investment casting process (shell creation, dewaxing and pouring). A separate study is under way to benchmark different rapid prototyping routes for their suitability for investment casting and analyze the techno-economic feasibility of the new methodology.
Figure 1: The ancient art of bronze casting [courtesy Rajan Industries, Swamimalai]: top left: proportions laid out in shastras; top right: cement molds for initial wax models; middle left: wax modeling and instruments; middle right: clay-covered molds are dried; bottom left: molds ready for dewaxing; bottom right: an as-cast idol.
Figure 2. Computer-aided technologies for casting development: top: haptic-based solid modeling; middle: solidification analysis of an investment cast alloy steel valve body; bottom: rapid prototype pattern and the corresponding casting.
Conclusion

The ancient art of bronze casting is a slow and cumbersome process involving individual attention to each casting starting from crafting the wax model to final finishing. The high content of skilled labour also makes the cost of such castings beyond the reach of most customers, and therefore mainly limited to export market. It is felt that there is a good scope for investigating the introduction of computer-aided tools, especially haptic-based modeling systems (useful for intricate shapes) and rapid prototyping systems (for converting the virtual models into actual wax models).

Modern engineers can also learn something important from the ancient practice. One difference is in the use of completely natural and recyclable materials in the entire process in the ancient method. Another important difference is in the notion of quality. In recent times, the definition of quality is moving from absence of defects (or conformance to specifications) to customer satisfaction and even delight (conformance plus). In this progression, the role of design and manufacturing engineer is becoming subservient to the notion of ‘customer is king’. In contrast, the ancient artisans were so focused on achieving perfection and were so proud of their work that any fault-finding by customer was inconceivable. In other words, self-satisfaction preceded customer satisfaction. This may be an important lesson to mull about, as the world is moving from an era of mass production towards an era of small lots and customization.

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References


About the speaker

Dr. B. Ravi (PhD, I.I.Sc. Bangalore) is an Associate Professor of Mechanical Engineering at I.I.T. Bombay and currently the coordinator of Manufacturing group. He has been working in intelligent CAD/CAM for casting for 15 years and his programs are used in several foundries. He has guided over 50 students, written 50 technical papers and given invited lectures in India, USA and Europe. He regularly conducts continuing education courses for practicing engineers and has guided many firms in exploring and adapting CAD/CAM tools. The I.I.Sc, Bangalore, Institute of Indian Foundrymen, Calcutta, World Foundry Organization, Paris, We Think for India Foundation and others have recognized his work with awards.