1. Metal Casting - Overview

In this chapter, we will first briefly review the history of metal casting, various cast metals, their applications, casting processes and foundry activities. This will be followed by emerging customer requirements, and the importance of product and tooling design.

1.1 History of Metal Casting

Casting is a 6000-year young process. It is mentioned in *Shilpashastra*, derived from *Sthapatyaveda* containing the principles of realizing all kinds of man-made structures, in turn is derived from *Atharvaveda*, one of the four principal *Vedas*. Earliest castings include the 11 cm high bronze dancing girl (Fig.1.1) found at Mohen-jo-daro (around 4000 BC) and the bronze frog found in Mesopotamia (3200 BC). The remains of the Harappan civilization contain kilns for smelting copper ingots and casting tools. Such castings were made by melting and 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. The earliest iron castings have been found in both India and China, around 2000 BC. Large scale state-owned mints and jewelry units have been mentioned in Kautilya's Arthashastra (circa 500 BC), which details 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 proved through recent excavations.

Fig.1.1: The ancient art of metal casting. Left top: Stone mold for coin casting; left bottom: ancient Egyptian foundry; right: bronze dancing girl.

The fifth century Iron Pillar of Delhi, which stands 23 feet, made of wrought iron with iron content of 99.72%, without showing any signs of rust is a remarkable example of the level of metallurgical science in ancient India. The Nataraja statues of Chola dynasty (9th century AD) stand testimony to the fine practice of intricate castings in mediaeval India. Most of these were made in Ashta Dhatu (essentially bronze) using the Lost Wax process. By this time, India was also producing very high quality steel. Various alloying techniques were in use. Abul Fazl in Aini Akbari mentions the coating of copper vessels with tin. Bidari, an alloy of copper, lead and tin developed in the Deccan, was also extensively used. Several writers, such as Dharmapal, have mentioned the quality and cost competitiveness of Indian foundry and forge industry. Captain Presgrave of the Sagar Mint wrote in his report after he wrought up the iron into bars and rods for an iron suspension bridge on which he was employed, that the "bar iron (is) of most excellent quality, possessing all the desirable properties of malleability, ductility at different temperatures and of tenacity for all of which I think it cannot be surpassed by the best Swedish iron". The Indian metallurgical science and casting technology was transferred to Europe through Portuguese explorers in 14th century AD, where it blossomed as a fine art. Vannocio Biringuccio, head of Papal Foundry in Rome (circa 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." The famous bronze castings of Perseus and Medusa (1540 AD) represent both Cellini's artistry and the capability of the casting process.

Table 1.1: Milestones in Indian iron and steel industry [SAIL India]

PERIOD	MILESTONES
300 BC	Porus presented Alexander 30 lbs of Indian iron. Kautilya (Chanakya) writes about minerals, including iron ores, and the art of extracting metals in 'Arthshastra'.
350 AD	A 8-metre wrought iron pillar erected near Delhi in memory of Chandragupta II. Another 16-metre iron pillar erected at Dhar (near Indore).
13th century	Massive iron beams used in the construction of the Sun temple, Konark
16th century	Indian steel known as 'Wootz' exported to Middle East and Europe
17th century	Manufacture of cannons, firearms and swords and agricultural implements. Suspension bridge built over Beas at Saugor with iron from Tendulkhma (MP). Iron smelter built at Porto Nova (Madras).
1870	Bengal Iron works established at Kulti.

1.2 Casting Production Worldwide

Nearly 65 million tons of cast components worth more than $100 billion are produced annually for automobile, industrial machinery, municipal fittings and many other sectors, by over 30,000 foundries worldwide. An even larger number of companies are involved in designing, machining, testing and assembling cast components and in related activities such as tool making and material supply.

According to the census of world casting production, the USA is the leading producer as well as consumer of castings followed by China, Japan, Germany and India (Table 1.1). The top ten producers together account for over 75% of the total production of castings as well as the number of foundries worldwide. Over the last ten years, the number of foundries in most countries has reduced, while the production has increased.

Table 1.2: Top ten producers of castings

COUNTRY	PRODUCTION (million tons)			NUMBER OF FOUNDRIES		
	2000	1997	1994	2000	1997	1994
USA	13.71	14.07	11.71	2950	2950	3100
CHINA	12.64	10.90	12.36	9374	10997	13934
JAPAN	5.97	6.96	6.68	650	1418	1428
GERMANY	4.33	3.93	3.48	719	780	889
INDIA	3.24	3.22	1.58	5000	6000	6000
FRANCE	2.49	2.27	2.03	465	507	507
ITALY	2.32	2.12	2.27	1110	428	594
UK	1.92		1.37	1170		283
KOREA	1.62	1.64	1.48	716	777	838
BRAZIL	1.57	1.58	1.49	900	997	934

Most foundries are of jobbing type, handling orders from different organizations. They are geared for quick development of new castings and large variations in order quantities. On the other hand, the castings produced in captive foundries are mainly consumed by the parent organization. The defining line is thinning as many jobbing foundries are now specializing in fewer products (say only cam shafts) and captive foundries are beginning to cater to organizations other than the parent, for better capacity utilization and to maintain a better competitive edge. Both types of foundries are moving towards increased levels of automation.

Foundries are also classified depending on capacity, as large, medium and small. The capacity may refer to either melting capacity (which depends on the furnaces installed and working) or actual production of good castings (which depends on order booking, overall yield and rejections). Large foundries can produce over 20,000 tons of castings per year, and are usually equipped with automated sand plants, molding, melting, pouring and fettling equipment. On the other hand, small foundries may have capacities as low as 500 tons per year with most of the operations being carried out manually.

1.3 Cast Metals and Applications

Virtually any metal or alloy that can be melted can be cast. The most common ferrous metals include gray iron, ductile iron, malleable iron and steel. Alloys of iron and steel are used for high performance applications, such as temperature, wear and corrosion resistance (Table 1.2). The most common non-ferrous metals include aluminum, copper, zinc and magnesium and their alloys. The production and application of ductile iron and aluminum castings are steadily increasing. Aluminum has recently overtaken steel in terms of production by weight. The consumption of magnesium alloys is rapidly increasing in automobile sector, owing its high strength to weight ratio, important for higher fuel efficiency.

Table 1.3: Major cast metals

METAL	USE	PROPERTIES	APPLICATIONS
Gray Iron	53%	Heat resistance, damping, low cost, high fluidity, low shrinkage.	Automobile cylinder block, clutch plate, brake drum, machine tool beds, housings
Ductile Iron	21%	Strength, wear and shock resistance, dimensional stability, machinability.	Crank shafts, cam shafts, differential housing, valves, brackets, rollers.
Aluminum	11%	Strength to weight ratio, corrosion resistance.	Automobile pistons, oil and fuel pumps, connecting rod, clutch housings.
Steel	9%	Strength, machinability, weldability, treatable.	Machine parts, gears, valves
Copper base	2%	High ductility, corrosion resistance.	Marine impellers, valves, hydraulic pump parts.

Castings can range in size: from a few grams (watch case) to several tones (marine diesel engines), shape complexity: from simple (manhole cover) to intricate (6-cylinder engine block) and order size: one-off (paper mill crusher) to mass production (automobile pistons). The desired dimensional accuracy and surface finish can be achieved by the choice of process and its control. Castings enable many pieces to be combined into a single part, eliminating assembly and inventory and reducing costs by 50% or more. Unlike plastics, castings can be completely recycled. Castings are used in virtually all walks of life. Major areas of applications are given below. The transport sector and heavy equipment (for construction, farming and mining) take up over 50% of castings produced.

Transport: automobile, aerospace, railways and shipping
Heavy equipment: construction, farming and mining
Machine tools: machining, casting, plastics molding and forming
Plant machinery: chemical, petroleum, sugar, paper, textile, steel and thermal.
Defense: vehicles, artillery, munitions and supporting equipment
Electrical machines: motors, generators and pumps.
Municipal castings: pipes, joints, fittings and valves.
Household: utensils and electric appliances.

1.4 Casting Processes

There are a large number of casting processes (see Fig.1.3). These can be classified based on the mold material, method of producing the mold and filling pressure (gravity, centrifugal force, vacuum, low pressure, high pressure). Metal molds are used in gravity and pressure die casting processes, suitable for producing a large number of components. In expendable mold processes (sand, shell and investment), a new mold is required for every casting or a bunch of castings with a common gating and feeding system. Expendable mold processes can be of either permanent pattern or expendable pattern type. Permanent pattern can be made from wood, metal and plastic to produce a number of molds. In expendable pattern process (investment process), each pattern produces only one casting. The four most popular processes are briefly described below, followed by a comparison of their capabilities (Table 1.4).

Sand Casting: In this process, sand mixed with binders and water is packed onto wood or metal pattern halves, removed from the pattern, assembled with or without cores, and metal is poured into resultant cavities. Molds are broken to remove castings. This is suitable for a wide range of metals (both ferrous and non-ferrous), sizes and shape complexity.

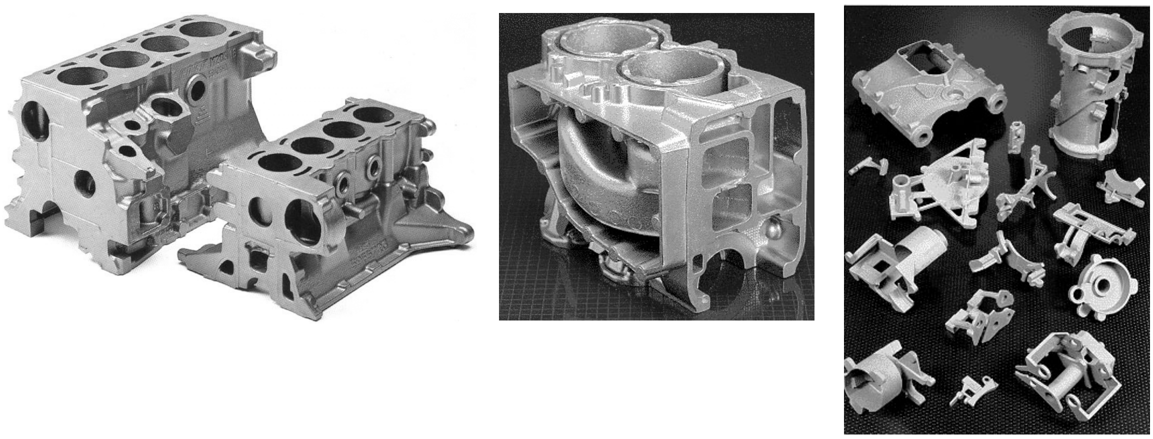

Fig.1.2: parts made by sand, die and investment casting processes.

Gravity Diecasting (also called permanent mold): Molten metal is poured under gravity into cast iron molds coated with a ceramic mold wash. Cores can be made of metal or sand. After solidification, molds are parted and castings are removed. This process is mainly suitable for non-ferrous metal castings, with medium size, complexity and thickness.

Pressure Diecasting: Molten metal is injected under pressure into hardened steel dies, often water-cooled. Metal cores are used to produce cavities and undercuts. After solidification, one half of the die is moved and castings are ejected. This process is mainly for non-ferrous castings with small to medium size, varying complexity and with thin walls.

Investment Casting: Wax is injected in a metal mold to make patterns, which are connected to a common sprue, repeatedly dipped in ceramic slurry and dried, followed by baking to remove the wax. The ceramic shell is preheated, filled with molten metal and broken to get the castings. This is suitable for any metal casting with small and intricate shape and thin walls.

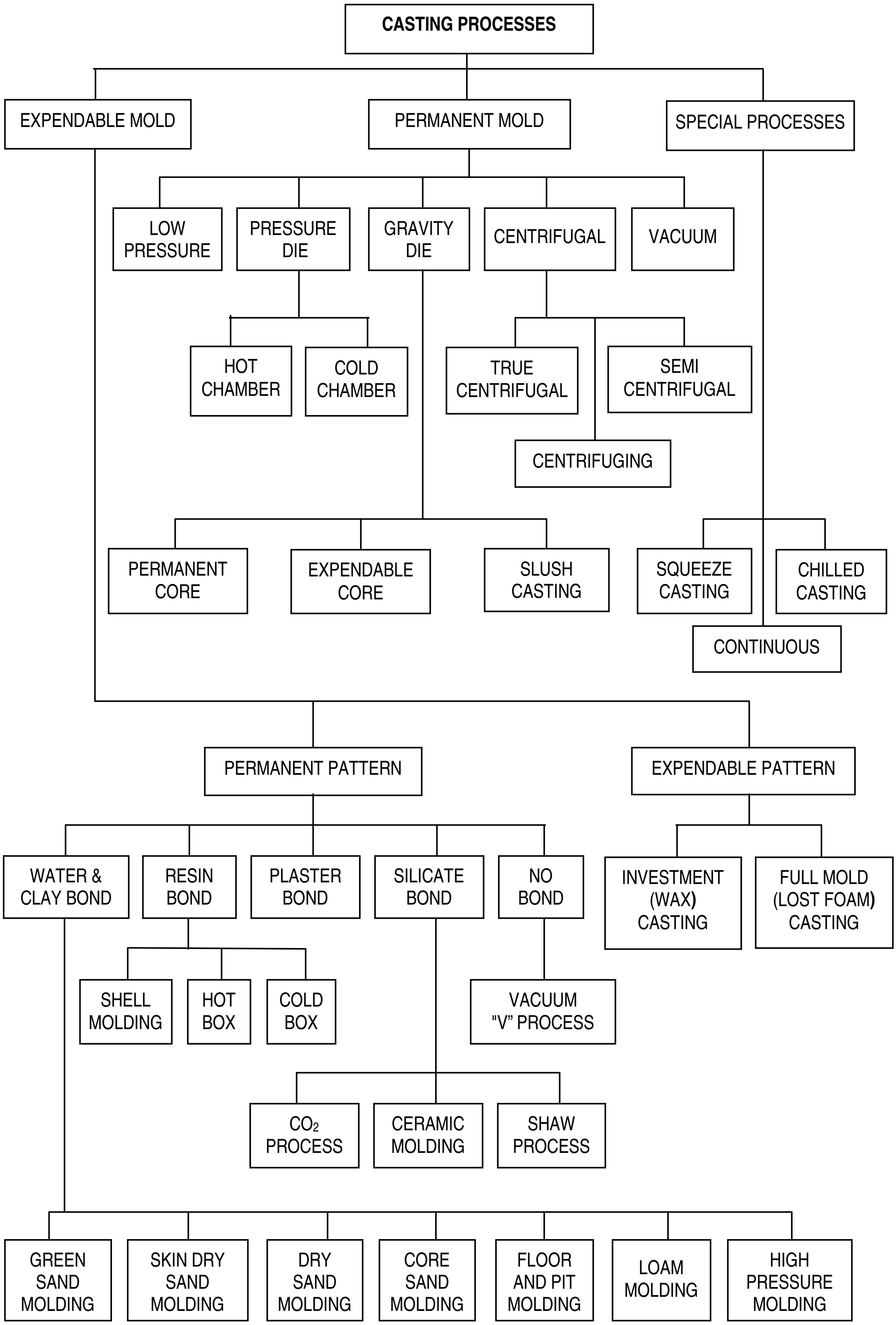

Fig.1.3: Hierarchical classification of various casting processes.

Table 1.4: Capabilities of major casting processes

Attribute \ Process	Sand	Gravity Die	HPDC	Investment
Maximum size	grams – tons	Up to 50 kg	up to 7 kg	up to 10 kg
Dim tolerance	> 0.6 mm	> 0.4 mm	> 0.05 mm	> 0.1 mm
Surface finish	> 200 RMS	> 150 RMS	> 30 RMS	> 60 RMS
Minimum thickness	> 6 mm	> 4.5 mm	> 0.8 mm	> 1.5 mm
Min order quantity	All	> 500	> 2500	< 1000
Sample lead time	2-6 weeks	8-20 weeks	12-22 weeks	8-10 weeks

Other important processes include: **centrifugal casting**, in which molten metal is poured into a rotating mold and centrifugal force pushes the metal against the mold; **lost foam or EPS or full mold** process, in which sand is packed around an expendable polystyrene pattern and the molten metal burns out the pattern as it fills the mold; **vacuum casting**, in which molten metal is forced into the mold under vacuum; and **squeeze casting**, in which semi-solid metal is forced under pressure into the mold, useful for composites.

1.5 Sand Casting Foundry

Sand casting is the most widely used process for both ferrous and non-ferrous metals. Depending on the molding method, it may be classified as green sand, dry sand, shell mold, etc. A typical green sand foundry involves three groups of activities. Pre-casting includes sand preparation, core making, molding and mold assembly. The casting stage involves furnace charging, melting, treatment (for example, inoculation), holding and pouring into molds, which are then left to cool. Post-casting involves shakeout, cleaning, fettling, shot-blasting and inspection. Further operations may include heat treatment and machining. These are briefly described here, along with the related equipment.

Sand Preparation: Molding sand should have good flowability (for better reproduction of pattern details), adequate green strength (to prevent its collapse during molding), dry strength (to prevent its collapse during mold filling), sufficient refractoriness (to withstand molten metal temperature), enough permeability (to allow entrapped air and gases generated inside the mold to escape) and collapsibility (for ease of shakeout). These are achieved by a suitable composition of the sand, binders, additives and moisture. The most widely available and economical is the silica sand. Special sands include zircon sand (lower thermal expansion, higher refractoriness and higher thermal conductivity), olivine sand (with properties in between silica and zircon sand) and chromite/magnesite sand (high thermal conductivity). The most widely used binder is bentonite clay (sodium or calcium bentonite), which imparts strength and plasticity to silica sand with the addition of water. Additives include coal dust (to improve surface finish by gas evolution at metal-mold interface), iron oxide (for high temperature resistance), dextrin (for improved toughness and collapsibility) and molasses (for high strength and collapsibility). Modern sand plants automatically carry out mulling, mixing, aeration and testing of the sand. Most of them also reclaim used sand through magnetic separation (to remove metal particles), crushing of lumps and removal of excess fines and bond (usually by washing in hot water or by mechanical impact).

Core Making: Cores are surrounded by molten metal, and have higher requirement compared to mold sand in terms of strength (to support its own weight and the buoyancy force of metal), permeability and collapsibility (especially for curved holes, otherwise they will be difficult to clean out). The most widely used binder for core sands is vegetable oil (linseed and corn oil, sometimes mixed with mineral oils), which is economical, but requires heating in an oven to about 240 C for 2-3 hours to develop its strength. Another widely used process uses sodium silicate binder mixed in dry sand free of clay; the sand mixture hardens immediately when CO_2 gas is passed through it. The process is highly productive. The core develops high compressive strength but has poor collapsibility. Other processes are based on organic binders; mainly thermosetting resins such as phenol, urea and furan. This includes hot box and cold box processes. The core sand mixed with binder is filled into a core box either manually or using a sand slinger. For higher productivity core blowing machines are used, in which the core boxes are mounted in the machine and core sand is forced and pressed into the core box under the stream of high velocity air. This is followed by appropriate heating of the core box to impart the desired properties to the core.

Molding: This involves packing the molding sand uniformly around the pattern placed in a mold box (or flask). Most foundries are equipped with jolt and squeeze machines operated by compressed air. The combination of jolting and squeezing action gives good compaction of sand near the pattern (by jolting the sand into crevices) as well as the top where the squeeze plate comes in contact with the mold. Many modern foundries are installing high pressure molding equipment, which use air impulse or gas injection to impact the sand on the pattern. These machines produce relatively less noise and dust compared to jolt and squeeze machines. A special type of high pressure molding machine is the flaskless molding machine pioneered by Disamatic, in which the parting plane is vertical and the mold cavity is formed between consecutive blocks of mold.

Melting: Most widely used melting equipment are cupula, oil/gas fired furnaces (including crucible and rotary furnaces), direct arc furnace and induction furnace. The cupola is the simplest and the most economical, and most suited for grey iron. Layers of pig iron, coke and flux (limestone) are charged into the cupola; air for combustion is blown through several openings (tuyeres). Use of hot blast of air and double row of tuyeres improves the efficiency of the cupola. Oil or gas fired crucible furnaces are suitable for melting small quantities of metal, usually non-ferrous. The crucible is usually made of graphite and clay. Rotary furnaces are made of steel shells lined with refractory, turning at a rate of 1-2 rpm. The charge is placed through a door in the middle; one end of the furnace is heated (by firing oil or gas) and the melt is taken out through the other end. Electric furnaces include direct arc and induction furnaces, which are more widely preferred by newer foundries owing to ease of control and high melting rate. In arc furnace, the heat is generated between the electrodes and transferred to the metal. In induction furnace, the heat is generated in the metal itself by eddy currents. Typical induction furnaces are of various types depending on the location of the induction coil (cored and coreless), and frequency of current (high or medium).

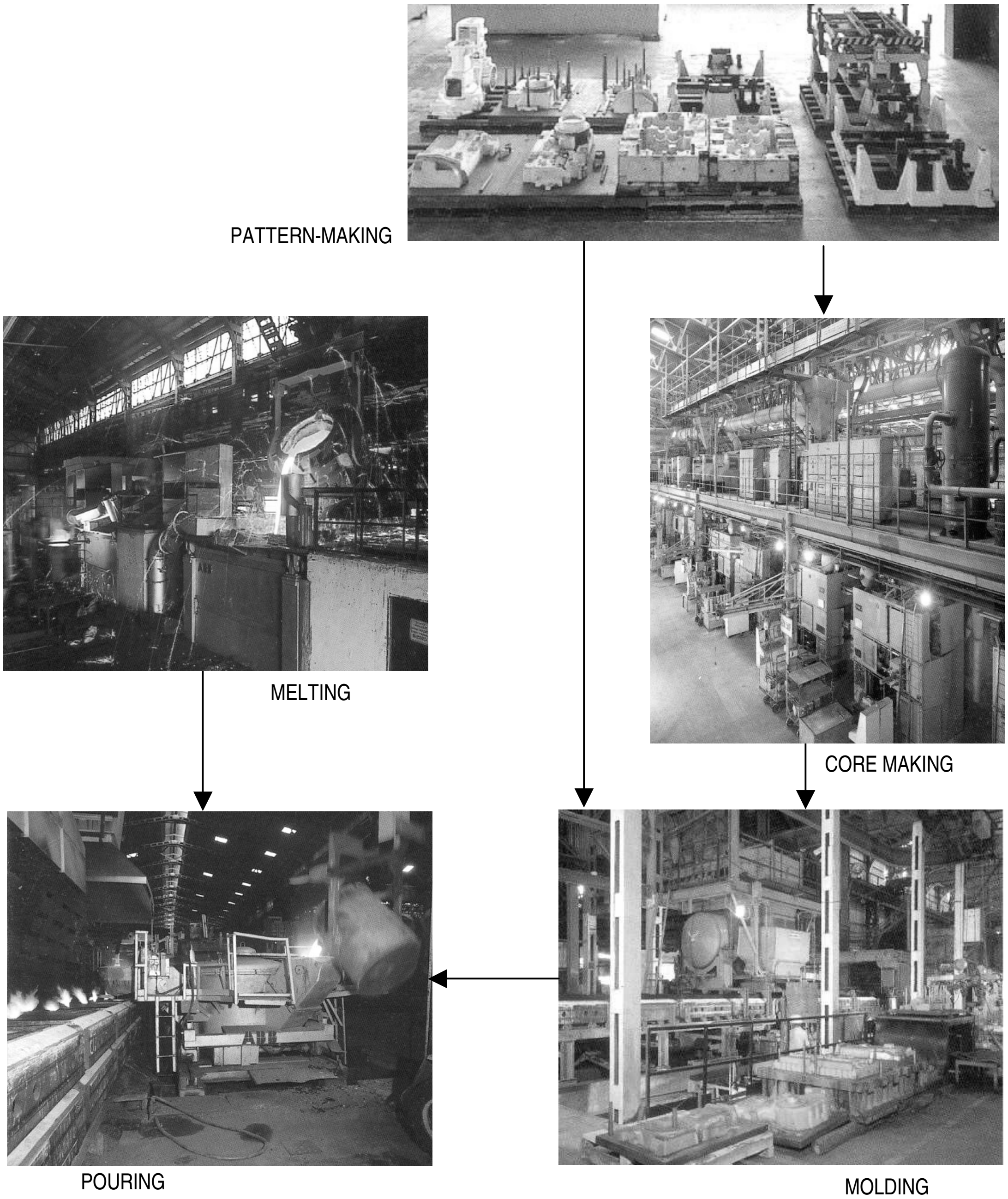

Fig.1.4: Key activities in sand casting (courtesy: Kirloskar Ferrous India Ltd.)

1.6 Casting Requirements

Over the last decade, there has been a steady increase in requirements of casting buyers (original equipment manufacturers and assemblers) in terms of quality assurance, shorter lead-time, smaller lot size and competitive pricing. Assemblers are eliminating inspection of incoming goods and expect the suppliers to be responsible for casting quality. The increasing use of NC machines for finishing operations requires dimensionally stable castings with uniform surface hardness to prevent damage to cutting tools. Because of shrinking product development cycles, foundries are expected to deliver the first sample in weeks instead of months. The adoption of Just-In-Time philosophy by assemblers to reduce their inventory costs requires foundries to deliver small lots and more frequently, while adhering to strict delivery schedules. The casting buyers want the foundries to continuously reduce their costs every year by adopting better technologies and methodologies. Increasing pressure from regulatory bodies in terms of energy conservation, environment protection and operational safety is of additional concern.

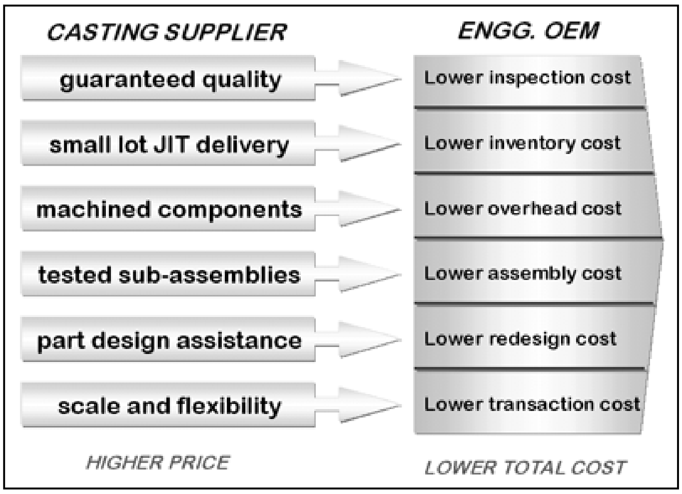

Fig.1.5: Better initial design and planning can reduce overall costs.

Many leading customers, particularly in the automobile sector, are moving toward long-term strategic partnerships with a few capable foundries instead of short term cost-based purchasing agreements with a number of foundries as in the past. This means that in order to survive, foundries have to offer dimensionally stable and sound castings (preferably with self-certification), ensure reliable on-time small lot delivery and promise continuous reduction in prices. Casting buyers and suppliers are now realizing that it is not possible to achieve the above, unless the product design and process capabilities are compatible with each other. This can be achieved only by integrated product and process development through close collaboration between casting buyers and suppliers.

Product design has a significant effect on its technical and economical value, since production methods can only be optimized within the framework established in this stage. Product design activity has three major steps which later affect manufacturing: conceptual design, detailed design and prototyping. Conceptual design involves deciding important features like overall shape, weight, size, property requirements (for example, wear and corrosion resistance) and production procedure (materials and processes), while achieving the stated functional requirements. In detailed design, material, dimensions, quality and production requirements are determined after product performance analysis with respect to its functional requirements. Physical prototypes are constructed for testing the product and evaluate different process parameters. Based on the results, the product design is improved, if necessary, and frozen for manufacturing.

Tooling development – patterns and core boxes (for sand casting) or dies (for die casting and investment casting) – is an essential but time-consuming activity. The average lead-time for the first good sample casting is 10-14 weeks, of which tooling development accounts for nearly 70%. Tooling design involves selection of the best orientation of part in the mold, determining the parting line, identifying cored features, design of cores and core boxes, design of pattern (including allowances) or die, mold cavity layout, design of risers to provide feed metal (number, location, shape, dimensions), design of gating channels to lead molten metal into the mold and cooling and ejection systems for dies. Tool manufacturing depends on its material, complexity, quality and time/cost considerations. Various methods include conventional machining combined with manual finishing, numerically controlled machining, rapid prototyping & tooling, or a combination of the above methods.

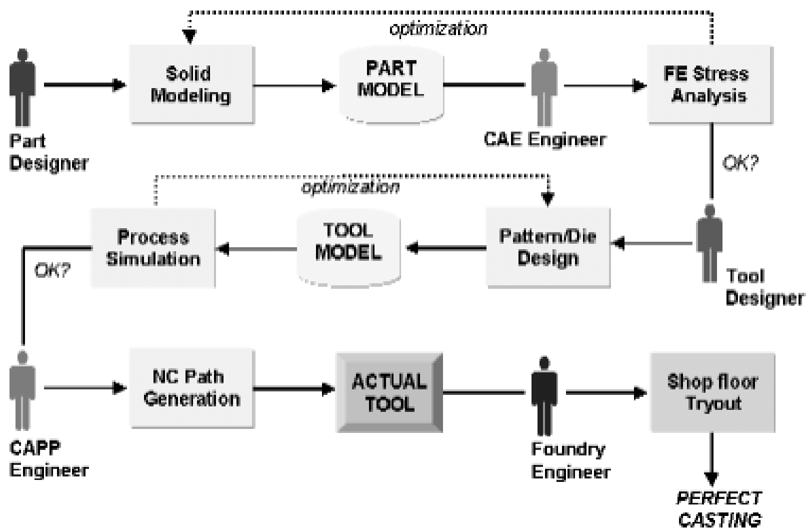

Fig.1.6: Computer-aided casting development

After tooling development, trial castings are produced in the foundry and inspected (using visual, destructive and non-destructive methods) for defects, if any. The tooling may be modified and process parameters may be tuned to improve casting quality and/or yield. Typically, 3-4 trials are required for most new castings, each trial taking up a working week or more. Even after several trials and approval of sample castings, there can be a high incidence of casting defects during regular production. Internal defects (such as shrinkage porosity and blow holes) are usually discovered at the machining stage in the assembler company, often leading to production bottlenecks. If such defects cannot be eliminated by modifications to process parameters or tooling design, then it becomes necessary to modify the product design, which is prohibitively expensive at this late stage. It is better to predict and prevent potential problems at the product design stage itself.