Technological Methods of Workpieces Manufacturing

Metal Casting

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
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Technological Methods of Workpieces Manufacturing
Metal Casting

MANUAL

for students in the «Technological Methods of Workpieces Manufacturing for Machine Parts» course

of First (Bachelor of Science) Level of Higher Education
13 «Mechanical Engineering» major
131 «Applied Mechanics» specialism

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Manual «Technological methods of workpieces manufacturing. Castings» provides the knowledge regarding different foundry processes and their industrial importance. It is considered the modern techniques of processing raw materials by casting as an important stage of solving the tasks of designing technological processes of manufacturing the parts.

Manual includes fundamentals of metal casting, the evolution of foundry industry, basic casting techniques, the metal casting operations, methods of manufacturing the cast blanks; the most rational variants of their manufacturing; equipment, tools and machining attachments for making workpieces of machine elements and parts in different process specifications and conditions. Also focused on efficient design of casting runner, riser, gating system with minimal casting defects and solidification process.

Recommended for students of first (Bachelor of Science) level of higher education, 13 «Mechanical Engineering» major, 131 «Applied Mechanics» specialism, and can also be useful for engineering and technical specialists of foundry technologies in the mechanical engineering industry.

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INTRODUCTION

Metal casting has been serving the manufacturing industry for years. It is used for manufacturing a range of products from being simple to exceptionally intricate. The challenges associated with the process have led to many advancements in metal casting technologies over time. During this period, different cast materials and casting processes have been evolved making it possible to design and manufacture almost any product with high quality. It is important to analyze the progress of metal casting in past, trends in the field at present, and envisage the future of these technologies for continuous improvement.

Casting technology encompasses many branches of science and engineering including physics, metallurgy, mechanical engineering, chemical engineering, and computational modeling. Chemical reactions involved in melting of metals and treating of liquid metals, formation of crystal structures, thermodynamic principles as applied to the determination of phase diagrams, design of gating and risering systems, and principles behind grain refinement and heat treatment all deal with some branch of science and engineering. Although there is still a lot of craft involved in the casting process, a good understanding of casting technology for the foundry engineer and technologist, mold maker, and pattern maker, would be useful to produce premium quality castings by minimizing casting defects. Application of solidification modeling in the design of gating and risering systems would eliminate the guesswork and contribute to the production of sound castings.

The engineer who designs a casting must have accurate information about the properties of the cast metals to be used. Manual may not be useful in the design of components that would lead to low mechanical properties. To provide a foundation for foundry work, coursework in the principles of metal casting finds a place in the educational preparation of student engineers. In addition, training offered by casting institutes or societies must incorporate developments in all aspects of metal casting such as alloy development, melting, melt treatment, sand, mold design, and gating and risering design.

This manual is addressed by explaining various types of casting defects along with their possible causes and remedies. The underlying idea behind this study is to let the readers ingrain the fundamental knowledge of metal casting technologies in all the above-mentioned areas so that the integrity and quality of castings can be enhanced.

1. EVOLUTION OF METAL CASTING INDUSTRY

Metal casting is one of the primitive manufacturing processes which was developed based on fire-using technologies (or pyrotechnologies). Initially, pyrotechnologies have been used to improve the workability of stone, make plaster by burning lime and produce ceramics by firing the clay.

Metalworking, however, started 10,000 years ago when the earliest metal objects are found to be wrought rather than cast [5, 36]. Evidence of such metal objects is found in the form of decorative pendants and beads which were formed by hammering native copper. Table 1 summarizes the advancements in metalworking over these 10,000 years.

Today, metal casting is a complex and intricate process that requires exact chemistry and flawless execution. While current methods may be relatively new when compared to the history of human civilization, the first casting of metals can actually be traced all the way back to around 4000 BC. In those times, gold was the first metal to be cast because of its malleability, and back then, metal from tools and decoration was reused because of the complications of obtaining pure ore.

Metal casting, on the other hand, dates back to 5000 and 3000 B.C, which refers to the Chalcolithic period during which metals were melted for castings together with the experimentation of smelting copper. Initial molds were made from smooth textured stones as shown in Fig. 1, resulting in fine cast products which could be witnessed in the museums and archeological exhibitions. Both single and multifaceted (carved on both sides of a rectangular piece of stone) molds were developed from stones to produce castings that are not necessarily flat. However, multifaceted molds were more popular for being portable and economical in terms of utilizing a suitable piece of stone [5].

Some historians believe that iron casting began in ancient China as early as 6000 BCE while others believe that only copper and bronze castings were being made at this time. However, evidence provided by archeologists contradicts both beliefs. Discovered by archeologists in what was then known as Mesopotamia, the earliest uncovered example of a cast component is a copper frog that dates to 3200 BCE. Although iron and other metals had been discovered, it was not until centuries later that they could be melted and poured into a mold, such as a casting.

Archeologists believe that iron was discovered by the Hittites of ancient Egypt somewhere between 5000 and 3000 BCE. During this time, they hammered or pounded the metal to create tools and weapons. They found and extracted it from meteorites and used the ore to make spearheads, tools, and other trinkets. Between 2000 BCE and 1200 BCE, the Hittites developed a process for smelting the iron – heating its ore to purify it – expanding its usability. For centuries, the production of iron remained a closely-held secret of the Hittite people until roughly 1000 BCE when Chinese metallurgists discovered the superiority and workability of iron.

Followed the by Chalcolithic period, the Bronze Age started in Near East around 3000 B.C. during which alloying elements were added to copper. The first bronze alloy reported was a mix of copper (Cu) with 4-12 %percent of arsenic (As), thus forming a silvery appearance of the cast surface as a result of inverse segregation of the arsenic-rich low-melting phase to the surface. Next, 5-10 % of tin (Sn) was added to copper which was advantageous to lower the melting point, improve strength, deoxidize the melt, and produce a fine and easily polished cast surface capable of reproducing the features of the mold with exceptional fidelity, often desirable for art castings.

The Bronze Age lasted for 1500 years during which mankind had its first exposure to elemental ores such as tin, copper and silver. Also, lost wax castings of small parts of bronze and silver, are reported during this age between 3000 and 2500 B.C. in the Near East region.

The earliest known casting in existence is a copper frog as shown in Fig. 2, probably cast in 3200 B.C. in the Mesopotamia region [6]. The intricate design and three-dimensional characteristics suggest that it was created using a sand casting process instead of using a permanent stone mold [36]. The beginning of the Bronze Age in the Far East was about 2000 B.C., a millennium after its emergence in the Near East region.

Some of the earliest examples of iron casting in ancient China are the four statues that stand outside of the Zhongyue Temple in Dengfeng. These statues were cast in approximately 1024 BC. Before this, Chinese metallurgists worked with bronze and copper to create cast components, which were largely used in the country’s agricultural industry. It was revolutionized when the iron plow was invented. It made turning over the soil much easier for farmers.

One of the biggest impacts that China had on the evolution of iron casting occurred in 645 BC when Chinese metallurgists began using sand molding. In this process, sand is tightly packed around an object, creating a mold. Then molten metal is poured into the mold to create a metal casting. The advantage of this process is the large variety of shapes and sizes that can be easily molded.

Table 1 - Development in use of materials and metal casting [5, 37]

Date	Development	Location
1	2	3
9000 B.C.	Earliest metal objects of wrought native copper	Near East
6500 B.C.	Earliest life-size statues, of plaster	Jordan
5000-3000 B.C.	Chalcolithic period: melting of copper; experimentation with smelting	Near East
3200 B.C.	A copper frog, the oldest known casting in existence, is made in Mesopotamia. Copper was a popular material for metalworking due to its high ductility (stretch)	Near East
3000-1500 B.C.	Bronze age: arsenical copper and tin bronze alloys. Bronze alloys are used in casting, offering key benefits such as low weight and a low melting point. Bronze tools and weapons are cast in permanent stone molds	Near East
3000-2500 B.C	Early use of investment (lost wax) casting for ornaments and jewelry. The lost wax casting of small objects	Near East
2000 B.C.	Bronze age	Far East
600 B.C.	Cast iron	China
233 B.C.	Iron ploughshares are cast	
500 A.D.	Cast crucible steel is produced	India
1200-1450 A.D.	Introduction of cast iron	Europe
1313	Development of the first bronze cannon in Ghent	China
1500s	Sand introduced as the mold material	France
1709 A.D.	Cast iron produced with coke as fuel, Coalbrookdale	England
1735 A.D.	The great bell of the Kremlin cast	Russia
1740 A.D.	Cast steel developed by Benjamin Huntsman	England
1779 A.D.	Cast iron used as an architectural material, Ironbridge Gorge	England
1809 A.D.	Development of centrifugal casting	England
1818 A.D.	Production of cast steel by crucible process	U.S.
1837 A.D.	Development of first molding machine	U.S.

Continue Table 1

1	2	3
1849	Development of a die casting machine	-
1863	Metallography of casting surfaces	England
1870	Development of sandblasting for large castings	U.S.
1876	Aluminum started to use as cast material	U.S.
1887	Development of oven for core drying	-
1898	Mold development with bonded sand	England
1899	Electric Arc Furnace for commercial production of castings	France
1900	Low-pressure permanent mold casting	England
1907	Heat treatment and artificial aging to improve cast aluminum alloys	Germany
1910	Match plates and Jolt Squeezing machines	-
1925	X-ray radiography for casting quality control	U.S.
1940	Chvorinov's Rule	-
1944	First heat-reactive, chemically-cured binder	Germany
1948	Ductile Iron castings in industrial applications	U.S.
1950s	High-pressure molding	-
Mid 1950s	Squeeze casting process	Russia
1960	Development of Furan as a core binder	-
1968	Cold box process for mass production of cores	-
1971	Vacuum forming or the V-process method	Japan
1974	In-mold process for ductile iron treatment by Fiat	U.S.
1948	Ductile Iron castings in industrial applications	U.S.
1980s	Development and commercialization of a solidification software	-
1988	Rapid prototyping and CAD/CAM technologies	-
1993	Plasma ladle refining (melting and refining in one vessel)	U.S.
Mid 1990s	Microstructure simulations	-
1996	Cast Metal Matrix Composites in automobile applications	England
End 1990s	Stress and distortion simulation of castings	-
2001	Software development by NASA and Department of Energy/OIT	U.S.
2016	Casting simulations coupled to mechanical performance simulations	-

The disadvantages are the unavoidability of defects and the fact that this process is quite labor-intensive. This is the earliest known use of this process and represents China's significant contribution to the history of iron casting. Casting was the main forming process in China with little evidence of other metalworking operations before 500 B.C. The complexity of antique cast bronze ritual vessels suggested that they must have been produced using the lost wax casting method.

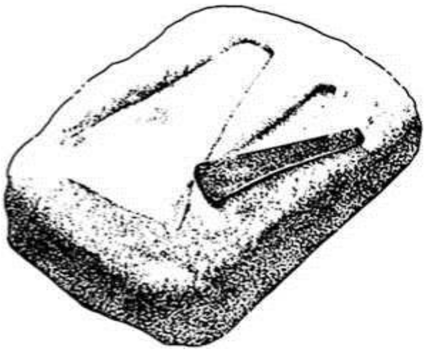


Figure1 - Mold prepared by smooth textured stone with an axe [5]

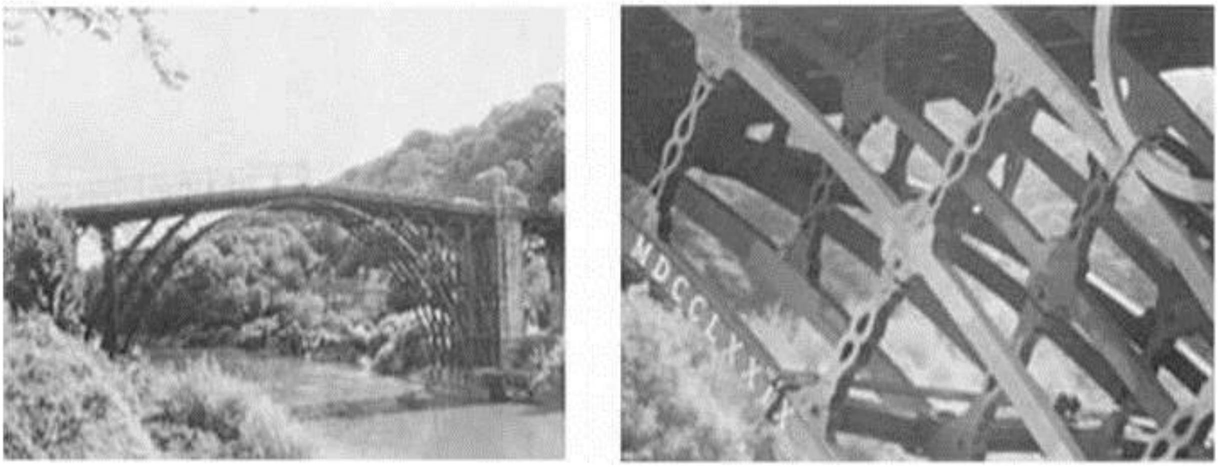
Figure 2 - The earliest known casting in existence "A Copper Frog", cast in 3200 B.C. [66]

In Europe, cast iron was introduced as a casting alloy between 1200 and 1450 A.D. The earliest evidence of cast products in Europe is a cast iron pipe used to transport water at the Dillenberg Castle in Germany. It was cast in 1455. Soon after this, in Burgundy, France, and England, cast iron was also used to make cannons during the Reformation of the 16th century.

In 1619, the first ironworks were established in North America by the Virginia Company of London. It was named Falling Creek Ironworks and was located near the James River. The colonists chose this location not only because of nearby ore deposits but also because it provided easy access to water for power and shipping-related needs. The surviving written records indicate that this facility was able to produce some iron. But historians believe that full production was never achieved.

In 1642, Saugus Iron Works, America's first iron foundry, was established near Lynn, Massachusetts. This was also the location where the first American iron casting, the Saugus pot, was made. Saugus Iron Works is now a national historic site, because of its landmark contribution to the manufacturing industry and the American industrial revolution.

Between the 15th and 18th centuries, some other important developments in the casting industry include where ut not limited to the introduction of sand as mold material in the 16th century, production of cast iron with coke as fuel at Coalbrookdale (1709), casting of the Great Bell of the Kremlin (1735), and the development of cast steel by Benjamin Huntsman (1740). The cast iron produced at Coalbrookdale was first used as an important structural material in building the famous iron bridge as shown in fig. 3 and in other architectural applications during that period.



a) b)

Figure 3 - The Iron Bridge (a) across the Severn River at Ironbridge Gorge (b) detail of the Iron Bridge showing the date, 1779 [1]

Iron's great impact on Britain can be attributed to a flurry of innovations that were introduced during the 1700s. The first of these occurred in 1709 when Abraham Darby became the first man to smelt iron with coke instead of charcoal in a coke-fired furnace. Coke is a solid fuel that is created by heating coal in the absence of air and is a key element in the history of iron casting. Coke was much cheaper and more efficient than charcoal. With the introduction of coke, it became possible and lucrative to use larger furnaces, which enabled large-scale production. Charcoal was too weak to support a heavy charge of iron in large quantities, but coke was much stronger. Although the challenge of brittle iron had not yet been solved, Darby's innovation had a big impact on the industry and inspired many other advancements.

The next innovation in iron casting history was the steam engine. It was invented in 1712 by an Englishman named Thomas Newcomen. At this time, the steam engine was primarily used to pump water out of coal mines. Coal was a key part of the iron casting process, so this invention was integral to the industry and the industrialization of England.

Between 1700 and 1750, Britain relied heavily on cast iron imports from Sweden, because it could not expand its capacity fast enough to meet the growing demand for cast iron. This was prior to Britain's industrial revolution. At that time, the iron manufacturing industry consisted of small, localized production facilities that had to be located close to the resources they needed, such as water, limestone and charcoal. That's because there were limited resources for transporting raw materials and finished goods.

At this time, furnaces were small, which meant that their production capacity was very limited. Although Britain had abundant iron ore reserves, the iron that could be produced from it was brittle pig iron of low quality with many impurities, which were caused by charcoal-fueled blast furnaces.

As a result, cast iron's usability was very limited. Most of the demand was for wrought iron, which was pig iron after its impurities were hammered out. But this took a long time to do, and imported wrought iron was less expensive. As a result, British iron at this time was only used for cheap items such as nails. However, iron would soon become the cornerstone of industrialization for the British economy, and by 1800, its leading export.

Between 1770 and 1790, Scottish inventor James Watt improved on Thomas Newcomen's work, making the steam engine capable of powering machinery, locomotives and ships. This further advanced the industry's speed and ability to transport raw materials and finished goods.

James Watt's breakthrough happened when he realized that the design of the steam engine wasted a great deal of energy because it repeatedly cooled and re-heated the cylinder. Watt introduced a design enhancement, the separate condenser, which avoided this waste of energy and radically improved the power, efficiency and cost-effectiveness of steam engines.

Eventually, Watt adapted his engine to revolutionize transportation, which had been a major limiting factor for growth within the iron manufacturing industry. Material transportation was finally made efficient and more economical than ever.

In 1783, Henry Cort developed two methods for extracting impurities from iron, turning it from pig iron to wrought iron, and allowing large-scale production of non-brittle iron. Pig iron is a term used to describe the crude and brittle iron that comes directly from the blast furnace. In 1783, Cort patented grooved rollers that allowed iron bars to be made more quickly with a more economic process he called the rolling technique. Previously used methods consisted of hammering or cutting strips from a rolled plate. In 1784, Cort patented the puddling process, which consisted of stirring molten pig iron on the bed of a furnace in which fire and hot gases swirling above the metal provide heat. This prevented the metal from coming in contact with the fuel.

As the iron was decarbonized by air, it became thicker and balls of "puddled" iron could be removed from the more liquid impurities that remained in the furnace. The puddled iron, like wrought iron, was tougher and more malleable than pig iron and could be hammered and finished with the grooved rollers that Cort had invented. The rollers helped to squeeze out impurities. Additionally, by forming the iron into bars, the metal became easier to use for the creation of finished goods. Cort's contributions to the industry allowed large-scale production of cast iron products because it no longer took so much time and manpower to rid the pig iron of its impurities.

Between 1793 and 1815, due to increased demand from the military, British iron production quadrupled. The sizes of blast furnaces increased, and Britain finally had production capabilities that could meet demand.

Cast materials and casting technologies progressed substantially from the 19th century onwards. A new method of centrifugal casting was developed in 1809 in England. However, in 1815, the War of 1812 ended, ushering in a period of peace. With the war's end came the decline of both the price and demand for iron. However, Britain had become the largest producer of ironworks in all of Europe. In addition, its economy and way of life were reshaped and revolutionized by innovations in iron casting.

In 1818 first U.S. cast steel was produced by the crucible process at Valley Forge Foundry. The extraction of aluminum from aluminum chloride is also reported during the same century. The first molding machine was developed by S. J. Adams Co. in Pittsburgh and was available by 1837.

The urge to further develop the casting process led to the development of a die casting machine to supply rapidly cast lead type for newspaper in 1849. Examination of castings was started by the development of metallography in 1863 which enabled foundry men to polish, etch and physically analyze the castings through optical microscopy. Next, sand blasting was developed for large castings in 1870. By 1876 aluminum was started to use as cast material and its first architectural application was reported in 1884 when a cast aluminum pyramid was mounted on the tip of Washington Monument. Some other developments during the 19th century are oven for core drying (1887), non-art application of lost wax casting method to produce dental inlays (1897), mold with bonded sand for salt-water piping system (1898), and electric arc furnace for commercial production of castings (1899).

In early 1900s, first patent for low pressure permanent mold casting was issued in England. American Foundry Association (AFS) produced rail wheels by centrifugal casting process for the first time. The advancement in the field continued with a die casting machine patented by H.H. Doehler patents in 1905. Heat treatment and artificial aging was proposed in 1907 to improve the properties of cast aluminum alloys. In 1910, jolt squeezing machining became possible through the development of matchplates. Another important development in 1915 was the experimentation on bentonite clay due to its exceptional high green and dry strength. In addition to that furnaces for non-ferrous melting were also developed during 1910s.

The quality of casting was first examined through X-ray radiography in 1925 after which all military aircraft castings had to pass X-ray inspection for acceptance by 1940. The development of mathematical relationships between casting geometry and solidification time was established by Chvorinov in 1940. Also, statistical process control was started to use for casting quality control and assurance in 1940s in the United States. The research on binders resulted in first heat-reactive, chemically-cured binder in Germany in 1944 for rapid production of mortar and artillery shells during World War II. By 1948, ductile iron was not just limited to laboratory castings and started to use as a cast material in industrial applications.

In order to increase the mold hardness (density), high pressure molding was experimented in 1950s. Hotbox system to prepare and cure the cores simultaneously was introduced in 1953 thereby eliminating the need of dielectric drying ovens. In mid 1950s, squeeze casting process originated from Russia. In addition to that a full mold process was developed in 1958, known as lost foam casting, where the pattern and gating systems were carved from expanded polystyrene (EPS) and placed into a green sand mold.

During 1960s, Furan was developed as a binder to be used in core production. Also shell flake resin was introduced in 1963 and it eliminated the need for different solvents. In 1968, a new method called “cold box process” was developed for mass production of cores in foundries. The late 20th century i.e.

1970-1999 brought more advancements to metal casting such as development of vacuum forming or the V-process method in 1971 to produce molds using unbonded sand by using vacuum. In 1974, Fiat developed an in-mold process for ductile iron treatment.

During 1980s, it was started to investigate the casting processes computationally an example of which is the development and commercialization of a solidification software. In late 1980s, casting solidification software gained acceptance in foundries resulting in optimization of quality and cost of casting process in virtual reality. An important development during this period was 3D visualization techniques followed by the rapid prototyping and CAD/CAM technologies in 1988 which significantly reduced the time of tool development.

Plasma ladle refining (melting and refining in one vessel) was introduced for the first time in 1993 at Maynard Steel Casting Company in Milwaukee, WI. In order to cast large components through lost foam castings, a low-expansion synthetic mullite sand is patented by Brunswick Corp. in 1994. Microstructure simulations in the mid 1990s enabled designers to analyze effects of metallurgy and predict and control mechanical properties of cast components.

Cast metal matrix composites (MMCs) were used in automobile applications such as brake rotors for the first time in 1996. In the same year, General Motors Corp. developed a non-toxic and recyclable, water-soluble biopolymer-based core sand binder. Casting simulation developed further towards the end of 1990s by stress and distortion simulation. As a result, generation and distribution of residual stresses in the cast component could be well understood which allowed to control casting distortion, reduce residual stresses, minimize defects such as hot tears and cracking, minimize mold distortion and improve mold life.

In 2001, a physics-based software was developed by NASA and Department of Energy/OIT capable of predicting the filling of EPS patterns and sand cores when process variable are changed.

In 2016, a new approach was developed which emphasized on developing an accept/reject criteria for castings by integrating simulation with mechanical performance simulations. Integrated simulations are currently being researched with an aim to improve integrity and quality, which eventually result in reliable operation of cast parts in service.

Today, nearly every mechanical device we use, from automobiles to washing machines are manufactured using metal parts that were created using the casting process. The difference between today’s cast metal products and those that were manufactured even 100 years ago is the precision and tolerances that can be achieved through the computerized automated design process, and modern methods for producing the detailed cores and molds. Modern-day metal casting represents innovation at work.

Throughout the centuries, various combinations of raw materials have been developed to produce various metal types. Some cast products are used in engines that require a high tolerance for heat and cold. Cast iron pipes must resist corrosion and high pressures. Other cast parts must be lightweight but durable. In many applications, parts are designed to allow for precise tolerance between expansion and contraction.

2. METAL CASTING AS A MANUFACTURING PROCESS

Metal casting is the manufacturing process of forming metallic objects by melting metal, pouring it into the shaped cavity of a mold and allowing it to solidify. The process of casting involves the basic operations of pattern making, sand preparation, molding, melting of metal, pouring in molds, cooling, shake-out, fettling, heat-treatment finishing and inspection, performed on foundries. What can be found in today's foundry that creates castings? Similar to a factory's production line, the manufacturing chain is composed of nine primary sections:

1. First, foundries melt metal to extremely hot temperatures. This requires heating raw metal and/or alloying elements into molten form so it can be poured into molds. In order to achieve these temperatures, specialized furnaces are used. Foundries may house different furnaces based on the type of material or casting process involved.

2. Some metals discharge quantities of hydrogen during cooling. Hydrogen bubbles escape to the top of the surface at the moment of cooling and solidification. This will create porosity on the object's surface and lead to mechanical and chemical deterioration of the object over time. To combat this, a foundry will employ various types of "degassing" equipment to measure and regulate the amount of hydrogen present in the object.

3. In order to create a casting from an original design, foundries require mold and pattern making equipment. Depending on the casting process involved, a foundry may offer several types of mold making systems. For example, sand casting requires specialized resin bonded sand molds. Investment casting requires the creation of wax patterns and ceramic molds. Die casting involves machining metals into molds using various alloys containing zinc, copper, lead, pewter, and more.

4. In foundry operations molten metal is transported, contained, or poured. Crucibles, robotic arms, and gravity induced pouring machines are used to move molten metal from one location to another. Metal workers will also pour molten metal by hand using ladles.

5. Once a mold solidifies, equipment is used to eject the final object from the mold. This requires the use of specialized cutting torches, saw blades, sledge hammers, or even knockout machinery to eject the casting from the mold.

6. Foundries also employ equipment used to heat treat metals in order to alter their physical properties. Using specific techniques in heating and cooling, a metal's properties are manipulated through annealing, case hardening, tempering, and quenching.

7. Once the casting is ready, its surface properties still require treatment. Excess mold media such as sand or metal particulate need to be removed. In this case, various surface treatments are used. This can include high powered compressed air or surface blasting with beads, metals, or other media.

8. Now that the casting is clean, final finishing takes place. The finishing process involves equipment for grinding, sanding, machining, painting, and welding to achieve whatever is requested by the customer.

Foundries are simply factories that provide steel casting services. Castings are the end product created by foundries. The tools, techniques, and processes used to make castings were berthed under the roof of the foundry. To this day, the pillars of our industry depend on foundries to create castings of all sizes and for every sector of our society.

Certain advantages are inherent in the metal casting processes. These may form the basis for choosing casting as a process to be preferred over other shaping processes. Some of the reasons for the success of the casting process are as follows [13, 18].

The most intricate of shapes, both external and internal, may be cast. As a result, many other manufacturing operations such as machining, forging, and welding may be minimized or eliminated.

Because of their metallurgical nature, some metals can only be cast to shape since they cannot be hot-worked into bars, rods, plates, or other shapes from ingot form as a preliminary to other processing. A good example of casting is the family of cast irons which are low cost, extremely useful, and exceed the total of other metals in tonnage cast.

Casting is a simplified manufacturing process. An object cast as a single piece often would otherwise require multiple manufacturing steps (stamping and welding, for example) to be produced any other way.

Casting can be a low-cost, high-volume production process, where large numbers of a given component may be produced rapidly. Typical examples are plumbing parts and automotive components such as engine blocks, manifolds, brake calipers, steering knuckles, and control arms.

Extremely large, heavy metal objects such as pump housings, valves, and hydroelectric plant parts which could weigh up to 200 tons may be cast. These components would be difficult or economically impossible to produce otherwise. Some engineering properties such as machinability, bearing, and strength are obtained more favorably in cast metals. In addition, more uniform properties from a directional standpoint can be expected, which is not generally true for wrought products.

Casting technology has progressed significantly, allowing products to be cast with very thin cross sections, often referred to as "thin-wall-casting"; such capabilities allow designers to reduce the casting weight that is often assumed necessary for production.

One has to consider the economic advantages of the casting process. In the aerospace industry, some components are still being machined out of forged or rolled pieces despite the fact such pieces can be cast more economically to meet the design criteria, especially with respect to strength and toughness. In some cases, the casting process may give way to other methods of metal processing. For example, machining produces smooth surfaces and dimensional accuracy not obtainable in any other way; forging aids in developing the ultimate tensile strength and toughness in steel; welding provides a convenient method of joining or fabricating wrought or cast parts into more complex structures; and stamping produces lightweight steel metal parts. Thus the engineer may select from a number of metal-processing methods, singularly or in combination, which is most suited to the needs of his or her work.

In comparison to other manufacturing processes like rolling, forging, welding, powder metallurgy, machining, pressing etc., the casting process has the following advantages:

1. There is no restriction on the type of metal or alloy for casting operation. In other processes like forging only a few ductile materials can be formed whereas a brittle metal like cast iron cannot be manufactured. For example, high alloy steels of high-melting temperature to low-melting aluminium alloys.

2. There is no restriction on the size of the component for casting. Items from a few grams to many tons weight are produced by casting process. There are severe problems in manufacturing larger parts by processes like powder-metallurgy, forging etc. For example, watch cases of few grams to rolling mill-housings, kiln-tyres of 50 tons each.

Extremely large, heavy metal objects such as pump housings, valves, and hydroelectric plant parts which could weigh up to 200 tons may be cast. These components would be difficult or economically impossible to produce otherwise.

3. The most intricate external and internal shapes can be formed by casting process, by suitable molding and core-making techniques. No such possibility exists in the other forming methods as rolling. For example, automobile cylinder blocks, carburetors, valve bodies.

4. Casting technology has progressed significantly, allowing products to be cast with very thin cross sections, often referred to as "thin-wall-casting"; such capabilities allow designers to reduce the casting weight that is often assumed necessary for production.

5. Because of their metallurgical nature, some metals can only be cast to shape since they cannot be hot-worked into bars, rods, plates, or other shapes from ingot form as a preliminary to other processing. A good example of casting is the family of cast irons which are low cost, extremely useful, and exceed the total of other metals in tonnage cast.

6. Some engineering properties such as machinability, bearing, and strength are obtained more favorably in cast metals. In addition, more uniform properties from a directional standpoint can be expected, which is not generally true for wrought products.

7. Casting is a simplified manufacturing process. An object cast as a single piece often would otherwise require multiple manufacturing steps (stamping and welding, for example) to be produced any other way.

8. A wide range of properties can be obtained in cast-parts by suitable choice of alloy and heat-treatment. Special properties like corrosion resistance, heat resistance, damping capacity, high strength etc., are possible.

9. Casting can be a low-cost, high-volume production process, where large numbers of a given component may be produced rapidly. Typical examples are plumbing parts and automotive components such as engine blocks, manifolds, brake calipers, steering knuckles, and control arms.

10. The casting process is economically suitable for both small quantity jobbing production as well as mass production by automatic machines. In the other process like rolling or forging, it is difficult to have flexibility in production-run without increasing cost. In the aerospace industry, some components are still being machined out of forged or rolled pieces despite the fact such pieces can be cast more economically to meet the design criteria, especially with respect to strength and toughness.

11. The casting process is still the cheapest available technique for forming many components from raw materials to the final usable stage. So it remains the fundamental manufacturing process inspire of many developments in other fields.

In some cases, the casting process may give way to other methods of metal processing. For example, machining produces smooth surfaces and dimensional accuracy not obtainable in any other way; forging aids in developing the ultimate tensile strength and toughness in steel; welding provides a convenient method of joining or fabricating wrought or cast parts into more complex structures; and stamping produces lightweight steel metal parts. Thus the engineer may select from a number of metal-processing methods, singularly or in combination, which is most suited to the needs of his or her work.

Casting process has the following disadvantages:

1. Metal casting involves melting of metal which is a high energy consuming process. Due to the growing cost of energy, many restrictions are being imposed on the energy-intensive metal casting units in several countries. For example, about 2000 kWh of power is required to produce a ton of finished steel castings.

2. Metal casting is still highly labour intensive compared to other processes. The productivity is thereby less than in other automatic processes like rolling.

3. The quantum of raw materials required for producing a ton of castings is quite high, needing exhaustive buildings, handling systems, large space and inventory costs. For example, for producing each ton of steel castings about 2,2 tons of metallics, 0,3 ton refractories, 1,2 ton of facing sand, 4 tons of backing sand are needed apart from many other minor materials.

4. The time required for the process of making castings starting from receipt of drawing is quite long compared to other processes like machining. On average, a medium-size ferrous casting takes 2 to 4 months for the first casting. Thus the entire cycle of order execution for castings can take between 3 months to one-and-a-half years depending on size, intricacy, composition, quantity to be cast, etc.

5. The working condition in foundries, due to heat, dust, fumes, heaps of scrap, castings, and, slag etc. at different stages, are quite bad compared to other process industries. The environmental pollution is high in metal casting industries. This is leading to closure of foundries in advanced countries like Germany, Switzerland etc., both by governmental legislation

and by unpopularity as a profession.

Despite this, the casting production is considered of the main factors influencing the development of world economy. Actual capacity of the world's casting production, which is higher than 91 millions metric tons per year (2020), is strongly diversified. The last decade brought significant changes in the Word map of the greatest casting producers. Globalization and transformation of economic systems is reflected by variations of foundry production in different countries, moreover the globalization of economy is regarded not only as a chance but also as a menace for the European foundries [24].

The most important research directions leading to further development of the foundry industry:

– development of new technologies and casting alloys,
– melting and liquid metal preparation,
– manufacturing of molds and cores,
– preparation of casting materials and composites,
– pouring, solidifying and cooling of casting,
– technological waste management,
– new production systems and quality control,
– sustainable development of foundry industry,
– energy and material efficient technologies.

European metal casting industry, just as most European and USA manufacturing, suffered greatly from the early in this decade. Moreover, substantial dynamics in the global economy, especially off-shore sourcing of cast metal components as well as the off-shore manufacturing of durable goods that require castings continue to profoundly reshape European metal casting industry. The effects of the recession were magnified by the influx of low-priced castings from off-shore sources including Brazil, India and particularly China. Nowadays it is becoming clear that economic trends and technological advances are creating an inflection point in the growth rate for cast metals components. The growth in the world economy demand for casting related to transportation and an industrialized infrastructure. Metal casters need to invest in technology and in people. A meaningful improvements in casting design, modeling, prototyping and production will be of the highest importance if foundries want to achieve increasing the capabilities and lower costs.

Finally foundries need to invest in people. The knowledge and skills needed to keep pace are changing even faster than the technology. Over the next 50 years, new skills will need to be developed every three to five years. Ongoing training and education will be a must for successful foundries.

These five trends are important for foundries in 2020.

Aluminum is displacing classic steel, the shortage of skilled workers is to be compensated for by progressive automation, and environmental protection is increasingly becoming a priority - this is only a small part of the topics that will dominate the foundry industry this year and in the years to come. We present you with five trends that you should keep an eye on this year.

1. Aluminum instead of steel.

Ever more products are produced with the material aluminum. There are numerous reasons for this: The automotive industry is just as pleased as the avionics sector when it comes to lighter components. However, the stability of aluminum is also a major factor. In mechanical engineering, this material is also used for mechanically demanding tasks.

In 2019, approximately six per cent more aluminum was produced than in the previous year. The higher price of the material becomes an ever smaller argument against this metal: The price of the finished product decreases due to advanced manufacturing methods and state-of-the-art machinery. Raw material prices have been comparatively high for years, but they are not affected by as many fluctuations as metal.

2. Automation due to lack of skilled workers.

Fewer and fewer people are working in the foundry industry. Harsh working conditions and falling training figures suggest further declines. In order to remain competitive, companies rely on semi-automated or completely autonomous systems to maintain or even increase their production.

By no means does this lead to further job cuts. Quite the opposite: Employees are able to invest more time in designing or testing instead of pressing buttons on machines, transporting raw materials or filling molten metal at high risk. At the same time, this increases the interest of younger generations to get involved in the design or the development of the foundry industry.

3. Digitization and Industry 4.0.

Sensors, linked machines and smart controls have no fear for the foundry either: Numerous production sites are already centrally connected. Not only foundries, but also customers and potential clients benefit from the data. Processes can be optimized with big data and possible bottlenecks and errors in the system can be detected at an early stage. Manual adjustments in the operating procedure are less necessary.

New technologies like virtual reality help companies to present themselves to the outside world. Thus, a virtual tour of the production halls becomes possible for everyone. Safety concerns are no longer necessary - furthermore, a presentation of the company is possible everywhere. Thanks to augmented reality, technicians can easily adjust or repair machines with a superimposed virtual image. Also virtual learning becomes easier with the new technologies. Meanwhile, numerous CAD programmers can also be used by way of 3D glasses to make prototyping more efficient.

4. Environmental protection and eco metals.

Foundries are considered to be amongst the most energy-hungry industries in Germany. A study by the Federal Environment Agency proves that the majority of foundries could get their energy requirements from renewable energies. For this, however, energy storage devices are necessary that can meet the enormous requirements for continuous day-night operation.

Through the use of more efficient casting molds, fewer raw materials are required, which also do not need to be transported. The energy requirement can be further reduced by using more efficient furnaces in order to make the entire production process more environmentally friendly.

5. Additive manufacturing.

Particularly for smaller cast products, things could change soon: More and more 3D printers are managing to deal with metals. Selective laser sintering (SLS) applies metal layer by layer in order to produce small components cost-effectively, quickly and more accurately than with conventional processes. Depending on the individual application, additive manufacturing offers various sizes ranging from half a cubic meter to entire warehouses that can be converted.

The innovative technology is already being used in projects that require only a small quantity of the final product. Structures, which would not be possible in normal casting, pose no problem for additive manufacturing either. For large quantities and parts with larger dimensions, not much will change for the time being.

The structure of the modern foundry industry is complex. Directly related to the traditional industry are the jobbing foundries with their capacity for undertaking work involving a wide range of sizes and designs. Quantity requirements are usually small and there is still some dependence on manual operations even though much of the heavy labor is removed by mechanical aids. At the opposite end of the scale are the specialized foundries, with their emphasis either on the mass production of a limited range of articles or on the use of a single special casting process. Many such foundries are captive to engineering organizations which incorporate castings in their own finished products.

The jobbing foundry is constantly presented with new problems in the molding of individual design features and in the determination of casting methods which will ensure a sound product at the first attempt. Whilst some minor design variations can be accommodated by recourse to the skill of the molder, the casting method must either be systematically evolved from an understanding of the underlying principles or must incorporate wide margins of safety at the risk of uneconomic production. This is where the introduction of computer simulation can save both costs and time by validating the intended casting method before any molten metal is actually poured.

In the mass production foundry, by contrast, the emphasis is upon close process control to maintain consistency in materials and procedures. Sophisticated pattern equipment eliminates the need for a high degree of skill in molding, whilst there is opportunity for progressive development of the casting method to reduce margins and achieve the most economic production.

This picture of the industry is necessarily simplified since many companies operate in several fields, with jobbing and mass production, conventional and highly specialized processes operating in parallel. Similarly, although most foundries base their activities on a limited range of alloys, for example grey cast iron or steel, copper base or die casting alloys, other firms produce several of these materials side by side.

3. METALS AND ALLOYS USED IN METAL CASTING

Different cast parts have different requirements. For example, some need to be as strong as possible, while others need to be as light as possible. The right metal for one part might not be the right metal for another, so it's important to know options before using cast parts. To get started, here is an overview of the eight most common metals used in manufacturing today: gray iron, white iron, ductile iron, stainless steel, carbon steel, copper-dazed alloy, nickel-based alloy, aluminum alloy.

Gray iron. Depending on the class of gray iron, different levels of machinability and strength can be achieved. Softer, more machinable gray iron can have tensile strengths as low as 20,000 psi. Tougher, less machinable iron can have tensile strengths triple that.

White iron is known for its excellent wear resistance. Some white irons have high levels of chromium or other alloys for increased performance of high-temperature service, or for corrosion resistance.

Ductile iron also ranges in strength, and has a higher level of tensile strength than gray iron. This wide range of strengths allows ductile iron to serve a wide variety of markets.

Stainless steel is the classification of steel that contains a chromium content of 10.5% or higher. It’s best known for its corrosion resistance, but also provides a high level of toughness. Higher levels of corrosion resistance can be reached using higher levels of chromium and molybdenum. Drawbacks to stainless steel include its lower level of machinability and medium tensile strength. These properties make stainless steel a great option for parts in oxidizing or corrosive environments.

Carbon steel has virtually no alloying elements. As a result, carbon steel offers very high level of machinability and weldability, while maintaining a high level of toughness.

Alloy steel is created by adding elements to carbon steel. These elements can include: manganese, nickel, molybdenum, silicon, vanadium, chromium, boron and titanium. Alloy steels have improved tensile strength, hardness and wear resistance, but sacrifice some weldability and toughness.

Copper-based alloys, in general, have a high level of corrosion resistance which can make these metals a great choice for long-term cost efficiency. Apart from that, the properties are dependent on what other elements are in the end combination. One of the most popular copper-based alloys is brass, which is a made up of copper and zinc as well as bronze – which is itself an alloy, generally made up of copper and tin and/or lead.

Nickel-based alloys have excellent corrosion resistance. Nickel is often coupled with copper, chromium, zinc, iron, and manganese to achieve different properties. The right combinations can have the tensile strength of carbon steel with good ductility and wear resistance. Alloys containing high levels of nickel are often used in chemical handling equipment.

Aluminum alloy, a popular choice in die casting, is a very castable alloy. Other great qualities of aluminum are its high level of machinability, which can reduce costs, and its high level of corrosion resistance, which allows aluminum to have a wide range of applications.

The following chart (Table 2) offers a comparison of characteristics of different alloys, including corrosion resistance, machinability, price, tensile strength, hardness, weldability, wear resistance and toughness.

Table 2 – Casting metal comparison chart

Characte-ristic	Gray iron	White iron	Ducti-le iron	Stain-less steel	Alloy steel	Carbon steel	Copper based alloy	Nickel based alloy	Alumi-num
Corrosion resistance	very low	very low	very low	high	low	low	high	very high	medi-um
Machina-bility	very high	high	high	low	medi-um	medi-um	high	low	high
Price	very low	very low	very low	high	medi-um	low	very high	very high	medi-um
Tensile strength	medi-um	very high	medi-um	very low	high	medi-um	low	medi-um	low
Hardness	high	very low	high	low	high	medi-um	low	mediu m	very low
Weld-ability	very low	very high	very low	medi-um	low	very high	very high	low	medi-um
Wear resistance	high	very low	medi-um	very low	high	medi-um	low	low	low
Tough-ness	very low	very low	very low	very high	low	high	medi-um	high	medi-um

4. FUNDAMENTALS OF METAL CASTING

4.1. Metal casting basics: molds, patterns, cores and gating and elements of a gating system

A mold is formed into the geometric shape of a desired part. Molten metal is then poured into the mold, the mold holds this material in shape as it solidifies. A metal casting is created. Although this seems rather simple, the manufacturing process of metal casting is both a science and an art. Let's begin our study of metal casting with the mold. First, molds can be classified as either open or closed. An open mold is a container, like a cup, that has only the shape of the desired part. The molten material is poured directly into the mold cavity which is exposed to the open environment.

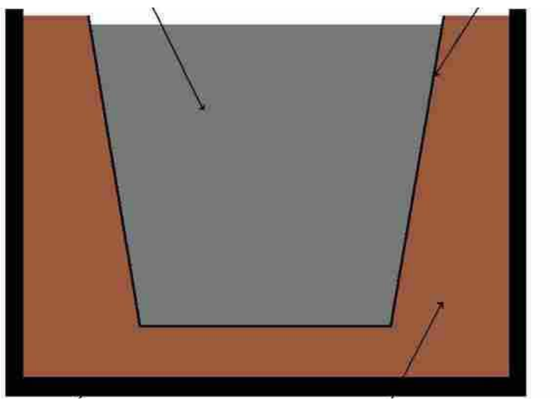


Figure 4 - Open mold

This type of mold is rarely used in manufacturing production, particularly for metal castings of any level of quality. The other type of mold is a closed mold, it contains a delivery system for the molten material to reach the mold cavity, where the part will harden within the mold. A very simple closed mold is shown in Figure 5. The closed mold is, by far, more important in manufacturing metal casting operations.

There are many different metal casting processes used in the manufacture of parts. Two main branches of methods can be distinguished by the basic nature of the mold they employ. There is expendable mold casting and permanent mold casting. As the name implies, expendable molds are used for only one metal casting while permanent molds are used for many. When considering manufacturing processes, there are advantages and disadvantages to both.

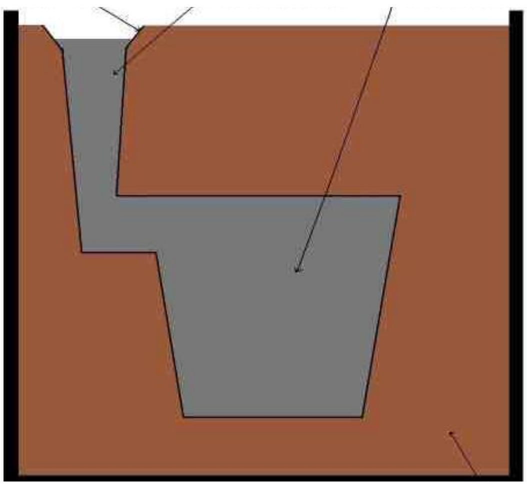


Figure 5 - Closed mold

Expendable mold

- Can produce one metal casting only.
- Made of sand, plaster, or other similar material.
- Binders used to help material hold its form.
- Mold that metal solidifies in must be destroyed to remove casting.
- More intricate geometries are possible for casting.

Permanent mold

- Can manufacture many metal castings.
- Usually made of metal or sometimes a refractory ceramic.
- Mold has sections that can open or close, permitting removal of the casting.
- Need to open mold limits part shapes.

Patterns.

Expendable molds require some sort of pattern. The interior cavities of the mold, in which the molten metal will solidify, are formed by the impression of this pattern. Pattern design is crucial to success in manufacture by expendable mold metal casting. The pattern is a geometric replica of the metal casting to be produced. It is made slightly oversize to compensate for the shrinkage that will occur in the metal during the casting's solidification, and whatever amount of material that will be machined off the cast part afterwards. Although machining will add an extra process to the manufacture of a part, machining can improve surface finish and part dimensions considerably. Also, increasing the machine finish allowance will help compensate for unknown variables in shrinkage, and reduce trouble from areas of the metal casting that may have been originally too thin or intricate.

Pattern material.

The material from which the pattern is made is dependent upon the type of mold and metal casting process, the casting's geometry and size, the dimensional accuracy required, and the number of metal castings to be manufactured using the pattern. Patterns can be made from wood, like pine (softwood), or mahogany (hardwood), various metal, like aluminum, cast iron, or steel. In most manufacturing operations, patterns will be coated with aparting agent to ease their removal from the mold.

Cores.

For metal castings with internal geometry cores are used. A core is a replica, (actually an inverse), of the internal features of the part to be cast. Like a pattern, the size of the core is designed to accommodate for shrinkage during the metal casting operation. Unlike a pattern, a core remains in the mold while the metal is being poured. Hence, a core is usually made of a similar material as the mold. Once the metal casting has hardened, the core is broken up and removed much like the mold. Depending upon the location and geometry of the core within the casting, it may require that it is supported during the operation to prevent it from moving or shifting. Structural supports that hold the core in place are called chaplets. The chaplets are made of a material with a higher melting temperature than the casting's material, and become assimilated into the part when it hardens. Note that when manufacturing a metal casting with a permanent mold process, the core will be a part of the mold itself.

The mold.

A typical mold is shown in Figure 6.

When manufacturing by metal casting, consideration of the mold is essential. The pattern is placed in the mold and the mold material is packed around it. The mold contains two parts, the drag (bottom), and the cope (top).

The parting line between the cope and drag allows for the mold to be opened and the pattern to be removed once the impression has been made.

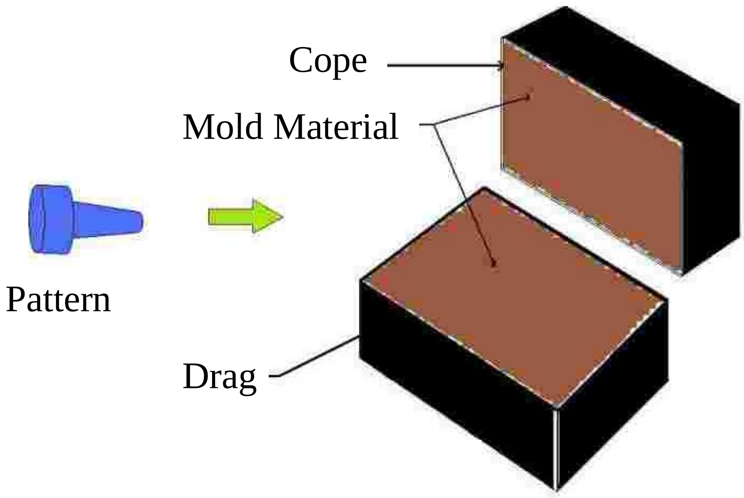


Figure 6 - Typical mold

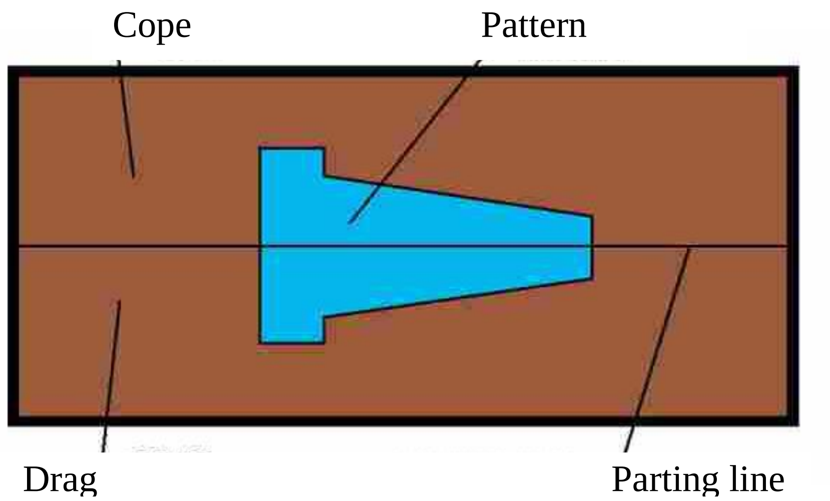


Figure 7 - Elements of the mold in manufacturing by metal casting

The core is placed in the metal casting after the removal of the pattern. Figure 8 shows the pattern impression with the core in place.

Now the impression in the mold contains all the geometry of the part to be cast. This metal casting setup, however, is not complete. In order for this mold to be functional to manufacture a casting, in addition to the impression of the part, the mold cavity will also need to include a gating system. Sometimes the gating system will be cut by hand or in more adept manufacturing procedures, the gating system will be incorporated into the pattern along with the part. Basically, a gating system functions during the metal casting operation to facilitate the flow of the molten material into the mold cavity.

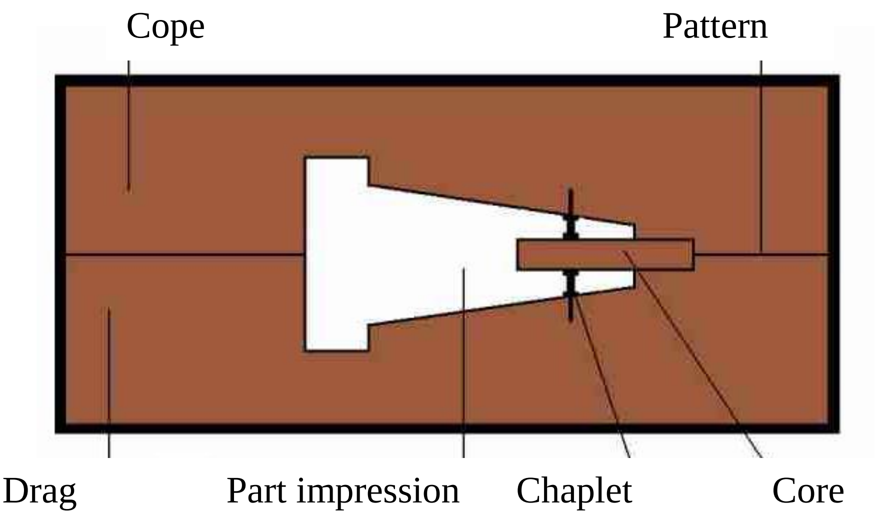


Figure 8 - Pattern impression with the core in place

Elements of a gating system.

Pouring basin.

This is where the molten metal employed to manufacture the part enters the mold. The pouring basin should have a projection with a radius around it to reduce turbulence.

Down sprue.

From the pouring basin, the molten metal for the casting travels through the down sprue. This should be tapered so its cross-section is reduced as it goes downward.

Sprue base.

The down sprue ends at the sprue base. It is here that the casting's inner cavity begins.

Ingate/choke area.

Once at the sprue base, the molten material must pass through the ingate in order to enter the inner area of the mold. The ingate is very important for flow regulation during the metal casting operation.

Runners.

Runners are passages that distribute the liquid metal to the different areas inside the mold.

Main cavity.

The impression of the actual part to be cast is often referred to as the main cavity.

Vents:

Vents help to assist in the escape of gases that are expelled from the molten metal during the solidification phase of the metal casting process.

Risers.

Risers are reservoirs of molten material. They feed this material to sections of the mold to compensate for shrinkage as the casting solidifies. There are different classifications for risers.

Top risers: Risers that feed the metal casting from the top.

Side risers: Risers that feed the metal casting from the side.

Blind risers: Risers that are completely contained within the mold.

Open risers: Risers that are open at the top to the outside environment.

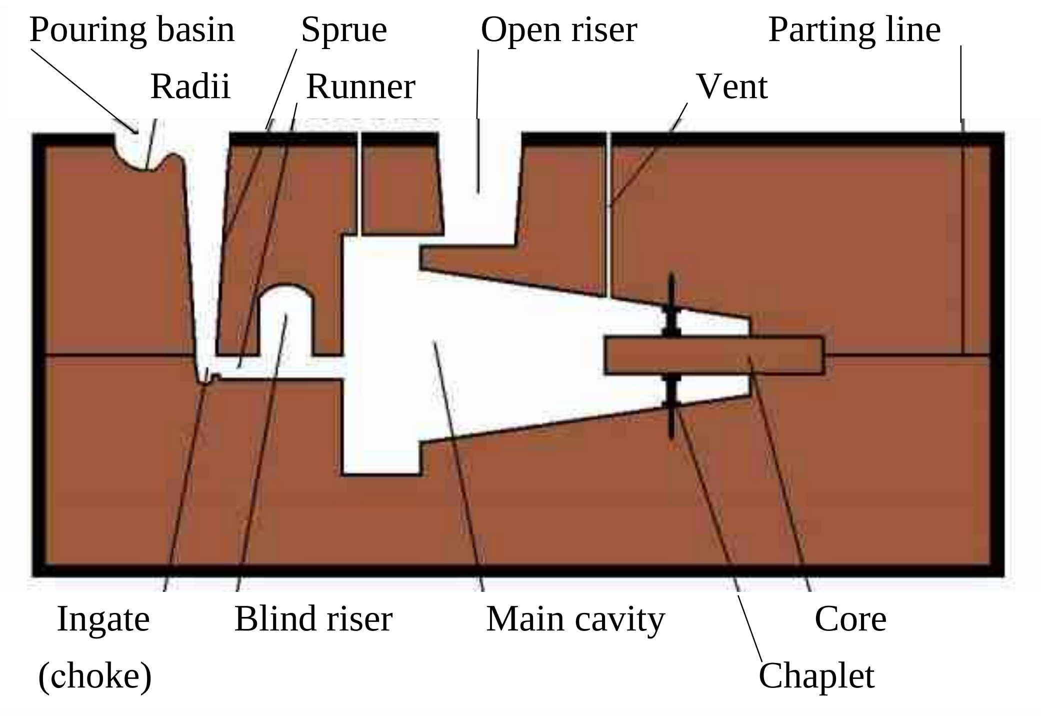


Figure 9 - Gating system for casting

Functional requirements of molding materials.

A foundry molding mixture passes through four main production stages, namely preparation and distribution, mold and core production, casting, and cleaning and reclamation. The property requirements of the materials are determined by molding and casting conditions; the preparation and reclamation stages will, however, also be considered, with particular reference to integrated sand systems.

The principal properties required at the molding stage are flowability and green strength: the former is a measure of the ability of the material to be compacted to a uniform density. The ideal balance of these properties depends largely upon the intended method of compaction, which may vary from hand ramming with tools to jolt, squeeze and impact ramming on molding machines and high velocity delivery on sand slingers and core blowers. High flowability is particularly necessary in the case of the non-selective ramming action of the molding machine, where the energy for compaction must be transmitted throughout the sand mass.

The need for green strength arises when the pattern is withdrawn and the mold must retain shape independently without distortion or collapse. The stress to which the molding material is subjected at this stage depends upon the degree of support from box bars, lifters and core irons and upon the shape and dimensions of the compact: less green strength is needed for a shallow core supported on a core plate or carrier than for a cod of sand forming a deep mold projection.

In many cases, however, dimensional stability and high accuracy may be achieved without the need for appreciable green strength, as when the mold or core is hardened in contact with the pattern surface, a common circumstance when modern bonding systems are employed.

Moving to the pouring stage, many molds are cast in the green state, but others, including most of those for heavy castings, are hardened to generate greater rigidity under the pressure and erosive forces of the liquid metal. This state was formerly achieved by the high temperature drying of clay bonded sands or the baking of traditional cores ands, but this has been largely superseded by the chemical hardening of sands containing reactive binders of the modern organic and silicate types. At this stage, therefore, dry strength i.e. strength in the hardened or dried condition is significant; even in greensand practice dry strength is required, to avoid friability should the mold partially dry out during standing before casting.

The other main requirement at the casting stage is for refractoriness, or the ability of the mold material to withstand high temperatures without fusion or other physical change. This property is primarily important in the manufacture of high melting point alloys, especially steel; for alloys of lower melting point, refractoriness can be subordinated to other requirements. In the production of very heavy castings, a considerable layer of molding material rises to a temperature at which normal mechanical properties are no longer the main criterion governing dimensional stability and resistance to contraction. Depending upon the mass of the casting, the sand may require an appropriate combination of high temperature properties, including hot strength to withstand distortion and the capacity for deformation to yield to the contraction of the casting. Collapsibility determines the readiness with which the molding material will break down in knockout and cleaning operations.

A further feature of the casting stage is the gas evolved and displaced from the mold. Much of this can be exhausted through open feeder heads and vents, but a large volume must also be dissipated through the pore spaces of the sand. This problem is greatest for greensands and core sands. The evaporation of each 1% of moisture from green molding sand can be shown to generate over 30 times its own volume of steam; this is paralleled in other types of sand by gases from volatilization and decomposition of organic compounds. To provide a path for the escape of gas, permeability is an essential property, giving protection against surface blows and similar defects. Fineness is required for the prevention of metal penetration and the production of smooth casting surfaces. Since both permeability and fineness are functions of grain size and distribution, the two properties are in conflict and a compromise is usually necessary.

Fineness may be achieved by using fine grained sands, by continuous grading or by the incorporation of filler materials, but all these measures also reduce permeability. An alternative approach is to use a highly permeable molding material and to obtain surface fineness by the use of mold coatings.

Molding materials need certain further qualities which are not necessarily measurable by standard tests. Examples are bench life, the ability to retain molding properties on standing or storage, and durability, the capacity to withstand repeated cycles of heating and cooling in integrated sand systems. It is thus evident that the qualities required in a molding material cannot readily be defined in terms of simple physical properties.

For complex aggregates bulk properties are of greater significance and some of these can be measured directly by simple tests upon sand compacts.

Other qualities are represented in specially developed empirical tests designed to reproduce conditions encountered in the foundry. These tests, in conjunction with the direct measurement of more fundamental characteristics such as mechanical grading and chemical composition, provide the basis for the control and development of molding material properties.

Many castings, including most of those made by machine molding, are cast in greensand molds, and the introduction of high pressure molding machines enabled even castings in the tonnage weight range to be produced to acceptable quality standards. There are strong economic incentives to use this low cost system, but hardened molds are preferred in many cases, particularly for heavier castings.

Bonding materials.

The function of the binder is to produce cohesion between the refractory grains in the green or hardened state. Since bonding materials are not highly refractory, the required strength must be obtained with the minimum possible addition.

Many substances possess bonding qualities, including clays, starch compounds, silicates and numerous organic resins and oils, both synthetic and natural: they may be used singly or in combination. Clay bonded sands are distinguished by the fact that they can be recirculated in closed systems and the bond regenerated by the addition of water; the action of most other binders is irreversible and the molding material has to be discarded after a single production cycle, although it is normally reclaimed at least in part for further use after suitable treatment.

4.2. The metal casting operation.
Pouring, fluidity, risers, shrinkage and other defects

In the previous section the fundamentals of the metal casting process, as the basic starting point for metal fabrication and part manufacture, were covered. Setup and design of a system to perform a casting operation was explained. Main topics were molds, patterns, cores, and the elements of a gating system. In this section we will explain the operation itself. We will begin by assuming that there is a mold with a proper gating system in place and prepared for the metal casting operation.

Pouring of the metal.

When manufacturing by metal casting, pouring refers to the process by which the molten metal is delivered into the mold. It involves its flow through the gating system and into the main cavity (casting itself).

Goal. Metal must flow into all regions of the mold, particularly the casting's main cavity, before solidifying.

Factors of pouring.

Pouring temperature.

Pouring temperature refers to the initial temperature of the molten metal used for the casting as it is poured into the mold. This temperature will obviously be higher than the solidification temperature of the metal. The difference between the solidification temperature and the pouring temperature of the metal is called the superheat.

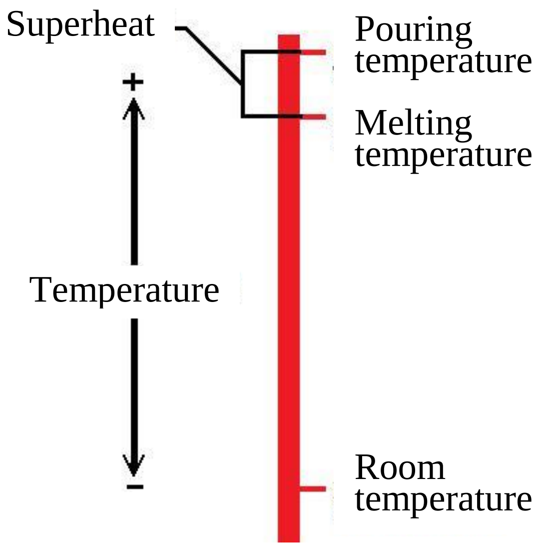


Figure 10 - Allocating temperatures

Pouring rate.

Volumetric rate in which the liquid metal is introduced into the mold. Pouring rate needs to be carefully controlled during the metal casting operation, since it has certain effects on the manufacture of the part. If the pouring rate is too fast, then turbulence can result. If it is too slow, the metal may begin to solidify before filling the mold.

Turbulence.

Turbulence is inconsistent and irregular variations in the speed and direction of flow throughout the liquid metal as it travels though the casting. The random impacts caused by turbulence, amplified by the high density of liquid metal, can cause mold erosion. An undesirable effect in the manufacturing process of metal casting, mold erosion is the wearing away of the internal surface of the mold.

It is particularly detrimental if it occurs in the main cavity, since this will change the shape of the casting itself. Turbulence is also bad because it can increase the formation of metal oxides which may become entrapped, creating porosity in the solid casting.

Fluidity.

Pouring is a key element in the manufacturing process of metal casting and the main goal of pouring is to get metal to flow into all regions of the mold before solidifying. The properties of the melt in a casting process are very important. The ability of a particular casting melt to flow into a mold before freezing is crucial in the consideration of metal casting techniques. This ability is termed the liquid metals fluidity.

Test for fluidity.

In manufacturing practice, the relative fluidity of a certain metal casting melt can be quantified by the use of a spiral mold. The geometry of the spiral mold acts to limit the flow of liquid metal through the length of its spiral cavity. The more fluidity possessed by the molten metal, the farther into the spiral it will be able to flow before hardening. The maximum point the metal reaches upon the casting's solidification may be indexed as that melts relative fluidity.

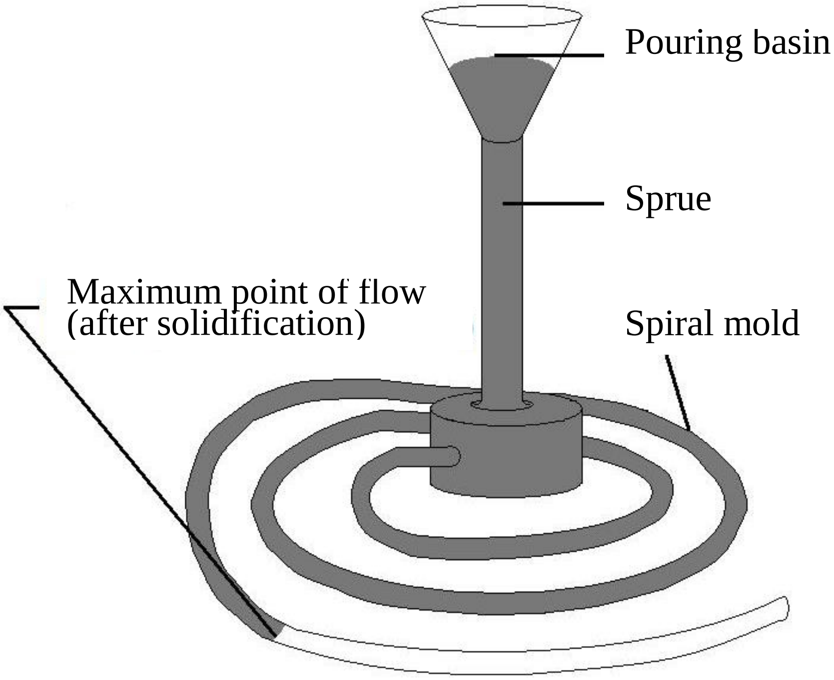


Figure 11 - Spiral mold test

How to increase fluidity in metal casting?

Increase the superheat. If a melt is at a higher temperature relative to its freezing point, it will remain in the liquid state longer throughout the metal casting operation, and hence its fluidity will increase. However, there are disadvantages to manufacturing a metal casting with an increased superheat. It will increase the melts likelihood to saturate gases, and the formation of oxides. It will also increase the molten metals ability to penetrate into the surface of the mold material.

Choose an eutectic alloy, or pure metal.

When selecting a manufacturing material, consider that metals that freeze at a constant temperature have a higher fluidity. Since most alloys freeze over a temperature range, they will develop solid portions that will interfere with the flow of the still liquid portions, as the freezing of the metal casting occurs.

Choose a metal with a higher heat of fusion. Heat of fusion is the amount of energy involved in the liquid-solid phase change. With a higher heat of fusion, the solidification of the metal casting will take longer and fluidity will be increased.

Shrinkage.

Most materials are less dense in their liquid state than in their solid state, and more dense at lower temperatures in general. Due to this nature, a metal casting undergoing solidification will tend to decrease in volume. During the manufacture of a part by casting this decrease in volume is termed shrinkage. Shrinkage of the casting metal occurs in three stages:

1. **Decreased volume of the liquid as it goes from the pouring temperature to the freezing temperature.**

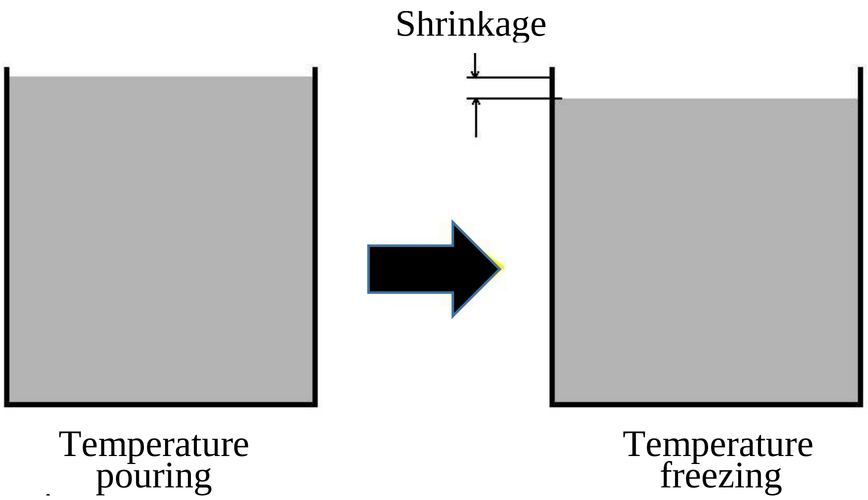


Figure 12 - The first stage

2. **Decreased volume of the material due to solidification.**

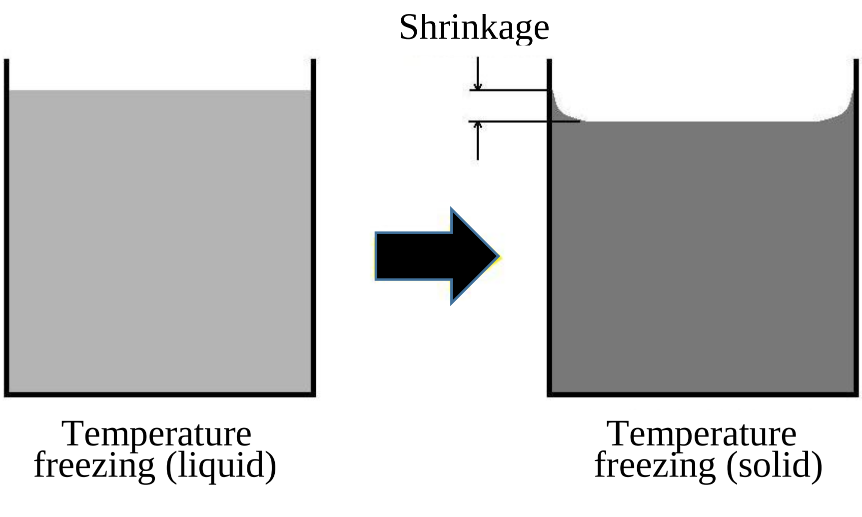


Figure 13 - The second stage

3. Decreased volume of the material as it goes from freezing temperature to room temperature.

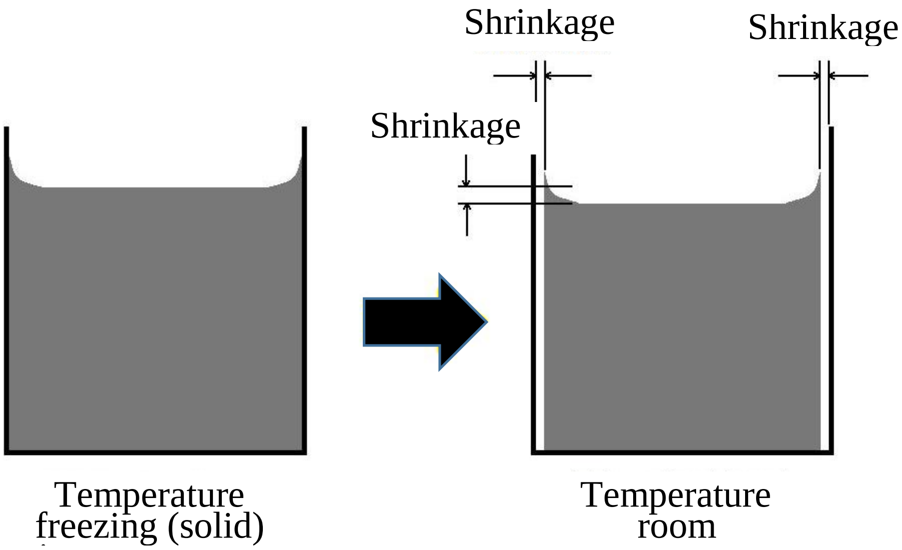


Figure 14 - The third stage

Risers.

When designing a setup for manufacturing a part by metal casting, risers are almost always employed. As the metal casting begins to experience shrinkage, the mold will need additional material to compensate for the decrease in volume. This can be accomplished by the employment of risers. Risers are an important component in the casting's gating system. Risers, (sometimes called feeders), serve to contain additional molten metal. During the metal's solidification process, these reservoirs feed extra material into the casting as shrinkage is occurring.

Thus, supplying it with an adequate amount of liquid metal. A successful riser will remain molten until after the metal casting solidifies. In order to reduce premature solidification of sections within the riser, in many manufacturing operations, the tops of open risers may be covered with an insulating compound, (such as a refractory ceramic), or an exothermic mixture.

Porosity.

One of the biggest problems caused by shrinkage, during the manufacture of a cast part, is porosity. It happens at different sites within the material, when liquid metal can not reach sections of the metal casting where solidification is occurring. As the isolated liquid metal shrinks, a porous or vacant region develops.

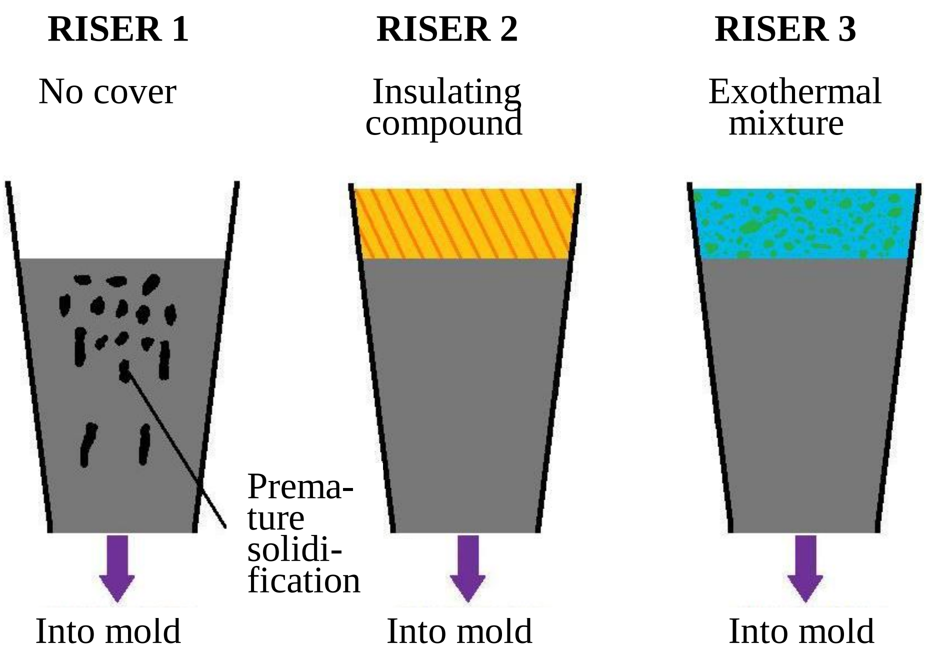


Figure 15 - Types of risers

Development of these regions can be prevented during the manufacturing operation, by strategically planning the flow of the liquid metal into the casting through good mold design, and by the employment of directional solidification. These techniques will be covered in detail in the gating system and mold design section. Note that gases trapped within the molten metal can also be a cause of porosity. The effects of gases while manufacturing parts by metal casting will be discussed in the gases section. Although proper metal casting methods can help mitigate the effects of shrinkage, some shrinkage, (like that which occurs in the cooling of the work metal from the top of the solid state to room temperature), can not be avoided. Therefore, the impression from which the metal casting is made is calculated oversized to the actual part, and the thermal expansion properties of the material used to manufacture the part will be necessary to include in the calculation.

Other defects.

The formation of vacancies within the work material due to shrinkage is a primary concern in the metal casting process. There are numerous other defects that may occur, falling into various categories.

Metal projections.

The category of metal projections includes all unwanted material projected from the surface of the part. The projections could be small, creating rough surfaces on the manufactured part, or be gross protrusions.

Cavities.

Any cavities in the material, angular or rounded, internal or exposed, fit into this category. Cavities as a defect of metal casting shrinkage or gases would be included here.

Discontinuities.

Cracks, tearing, and cold shuts in the part qualify as discontinuities. Tearing occurs when the metal casting is unable to shrink naturally and a point of high tensile stress is formed. This could occur, for example, in a thin wall connecting two heavy sections. Cold shuts happen when two relatively cold streams of molten metal meet in the pouring of the casting. The surface at the location where they meet does not fuse together completely resulting in a cold shut.

Defective surface.

Defects effecting the surface of the manufactured part. Blows, scabs, laps, folds, scars, blisters, etc.

Incomplete casting.

Sections of the metal casting did not form. In a manufacturing process causes for incomplete metal castings could be; insufficient amount of material poured, loss of metal from mold, insufficient fluidity in molten material, cross section within casting's mold cavity is too small, pouring was done too slowly, or pouring temperature was too low.

Incorrect dimensions or shape.

The metal casting is geometrically incorrect. This could be due to unpredicted contractions in the part during solidification. A warped casting. Shrinkage of the metal casting may have been miscalculated. There may have been problems with the manufacture of the pattern.

Inclusions.

Unwanted particles contained within the material act as stress raisers, compromising the casting's strength. During the manufacturing process, interaction of the molten metal with the environment, such as the mold surfaces and the outside atmosphere, (chemical reactions with oxygen in particular), can cause inclusions within a metal casting. As with most casting defects, good mold maintenance and process design is important in their control.

4.3. Gases in metal casting.
Gases during the manufacture of a casting

The molten metal used during the casting process may trap and contain gases. There are various reasons that gases are absorbed into the metal melt during manufacture. Turbulent flow of the casting material through the system may cause it to trap gas from the air. Gases may be trapped from material or the atmosphere in the crucible when the melt is being prepared. Gases may be trapped from reactions between the molten metal and the mold material.

Since liquid metal has a much higher solubility than solid metal, as the casting solidifies these gases are expelled. If they can not escape they may form vacancies in the material, causing porosity in the metal casting.

Whether a vacancy in a cast material is a result of gases or shrinkage is sometimes hard to tell. If the vacancies are spherical and smooth they are most likely a result of gases. Angular and rough vacancies are most likely a result of shrinkage. Gross absences of material within the metal casting are a result of shrinkage.

Prevention of gas defects when manufacturing a part by casting:

- Gases being expelled by the material during solidification can be eliminated by a proper venting system in the mold. This can be planned out during the manufacturing design phase of the metal casting process.
- Mitigating the amount of turbulence in the fluid flow will reduce gas absorption into the metal.
- Removal of slag will help eliminate gases and other impurities in the casting.
- Gases may be removed by flushing a metal melt with inert gas.
- Elimination of gases may also be accomplished by pouring the metal casting in a vacuum.

Material selection.

The selection of proper materials is important in the design of a metal casting process. Here are a few things to remember when selecting manufacturing materials.

1. Metals may react a certain way with other materials they encounter during the casting process. This should always be a consideration. For example, liquid aluminum will react readily with iron. Iron ladles and

surfaces contacting the molten aluminum can be covered with a spray on ceramic coating to prevent this.

2. When selecting a type of manufacturing process, remember that some materials may be more applicable to different metal casting techniques than others.

3. Knowing the specific heat of the mold and that of the metal used for the casting will be influential in controlling the thermal gradients in the system.

4. Section of casting metal will factor heavily on the melt's fluidity.

5. A material with a high heat of fusion will take longer to solidify and may improve flow characteristics within the casting.

6. When manufacturing a casting with a metal alloy that freezes over a temperature range, problems may occur due to the solid phase interfering with the liquid phase, both of which will be present within the temperature range. To help reduce this problem, a metal alloy with a shorter solidification temperature range may be selected to manufacture the casting. Or select a mold material with a high thermal conductivity, which could reduce the time spent in the solidification range by increasing the cooling rate.

4.4. Metal casting design.
Mold and gating system design, directional solidification, and troubleshooting

In the previous sections we discussed the fundamental aspects of manufacturing parts by metal casting. We covered the creation of patterns, and the setup of the mold and gating system. Also we discussed the metal casting operation itself, including the pouring of the molten material into the mold, the elements and functions of the different parts of the mold during the manufacture of the cast part, and the problems and possible defects encountered during the employment of the manufacturing process of metal casting. In this section we will examine the specifics of good mold and gating system design in order to manufacture higher quality metal castings and minimize defects that may occur during the casting process. This section will be useful to those designing a system to manufacture a part by metal casting, or to help as a troubleshooting guide for improvement upon an existing system.

Gating system and mold design.

When selecting to manufacture a part by casting one must consider the material properties and possible defects that this manufacturing process produces. The primary way to control metal casting defects is through good mold design considerations in the creation of the casting's mold and gating system. The key is to design a system that promotes directional solidification. Directional solidification, in casting manufacture, means that the material will solidify in a manner that we plan, usually as uniformly as possible with the areas farthest away from the supply of molten metal solidifying first and then progressing towards the risers. The solidification of the casting must be such that there is never any solid areas that will cut off the flow of liquid material to unsolidified areas creating isolated regions that result in vacancies within the casting's material, as discussed in the Metal Casting Operation section and shown in Figure 16.

It is important to create an effective manufacturing process. Gating system design is crucial in controlling the rate and turbulence in the molten metal being poured, the flow of liquid metal through the gating system, and the temperature gradient within the metal casting.

Hence a good gating system will create directional solidification throughout the casting, since the flow of molten material and temperature gradient will determine how the metal casting solidifies.

When designing a mold for a metal casting or trying to fix or improve upon and existing design you may want to consider the following areas.

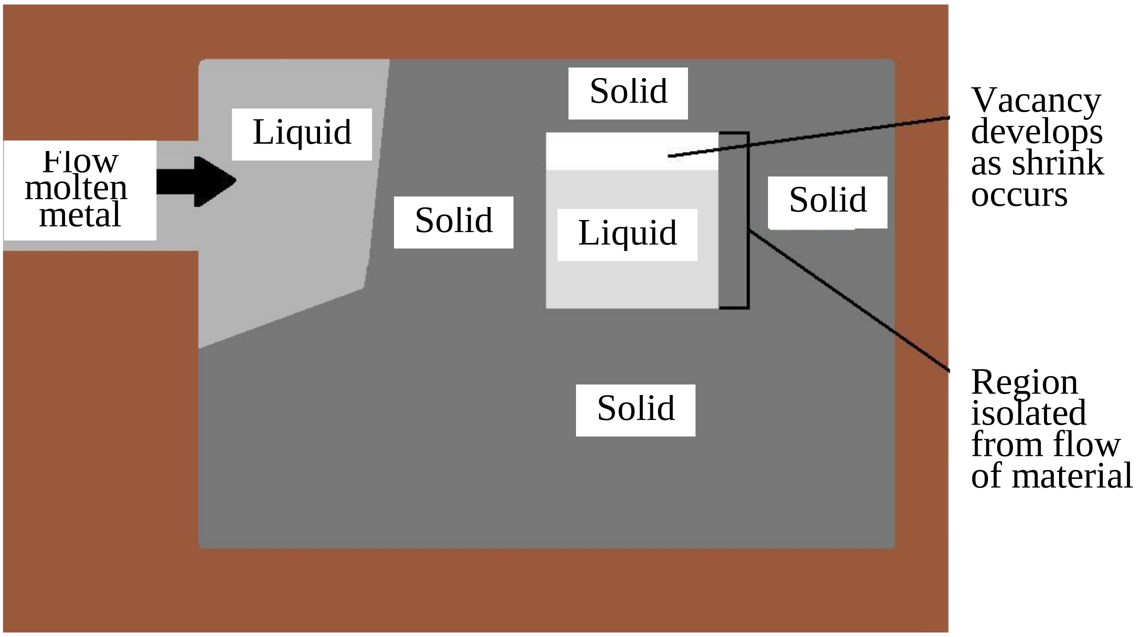


Figure 16 - Liquid and solid areas of material

Insure that you have adequate material.

This may seem very obvious, but in the manufacturing of parts many incomplete castings have been a result of insufficient material. Make sure that that you calculate for the volume of all the areas of your casting, accounting for shrinkage.

Consider the superheat.

Increasing the superheat, (temperature difference between the metal at pouring and freezing), as mentioned previously can increase fluidity of the material for the casting, which can assist with its flow into the mold.

This causes a compromise to the manufacturing process. Increasing the superheat has problems associated with it, such as increased gas porosity, increased oxide formation, and mold penetration.

Insulate risers.

Since the riser is the reservoir of molten material for the casting, it should be last to solidify. Insulating the top as mentioned earlier, shown in figure 13, will greatly reduce cooling in the risers from the steep temperature gradient between the liquid metal of the casting, and the room temperature air.

Consider V/A ratios.

In casting manufacture, V/A ratio stands for volume to surface area or mathematically (volume/surface area). When solidification of a casting begins a thin skin of solid metal is first formed on the surface between the casting and the mold wall. As solidification continues the thickness of this skin increases towards the center of the liquid mass.

Sections in the casting with low volume to surface area will solidify faster than sections with higher volume to surface area. When manufacturing a part by metal casting consideration of the of V/A ratios is critical in avoiding premature solidification of the casting and the formation of vacancies.

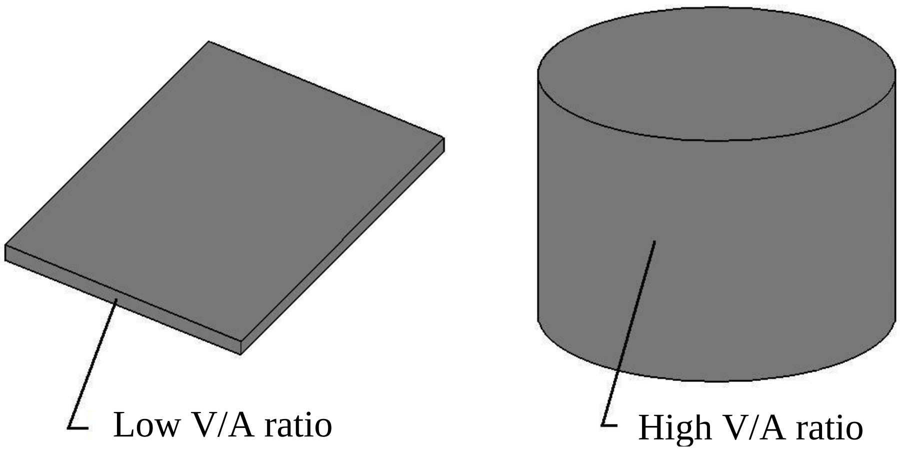


Figure 17 - Low and high V/A ratio

Heat masses.

Avoid large heat masses in locations distant to risers. Instead, locating sections of the casting with low V/A ratios further away from the risers will insure a smooth solidification of the casting.

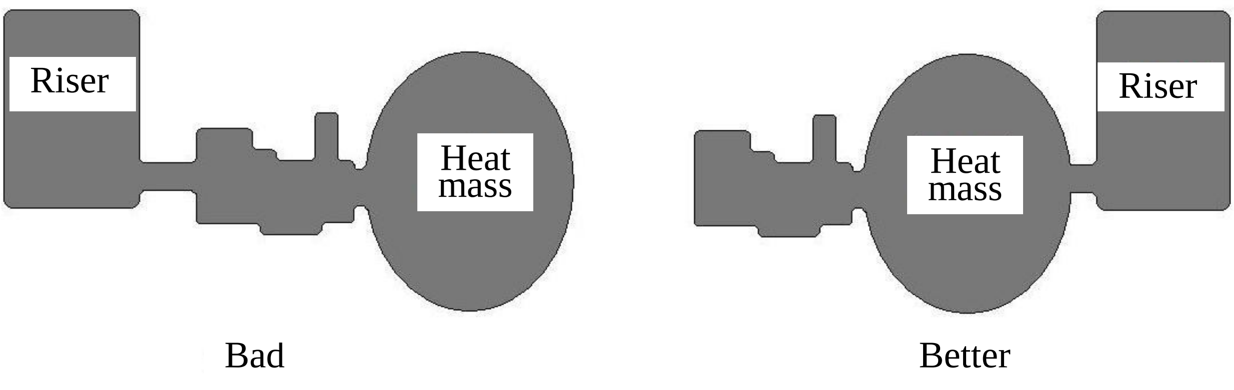


Figure 18 - Locating sections of the casting

Sections of the casting.

The flow of material is very important to the manufacturing process. Do not feed a heavy section through a lighter one.

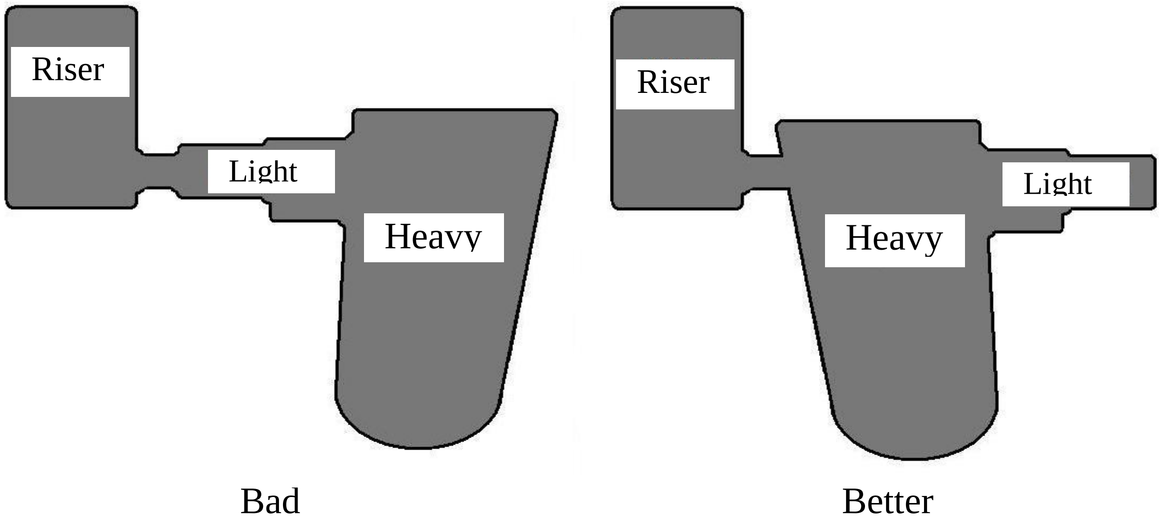


Figure 19 - Sections of the casting

Be careful with consideration to L, T, V, Y and + junctions.

Due to the nature of the geometry of these sections it is likely that they will contain an area where the metal casting's solidification is slower than the rest of the junction. These hot spotsare circled in white in Figure 20. They are located such that the material around them, which will undergo solidification first, will cut off the hot spots from the flow of molten metal. Some possible design alternatives are shown in Figure 20. These should reduced the likelihood of the formation of hot spots.

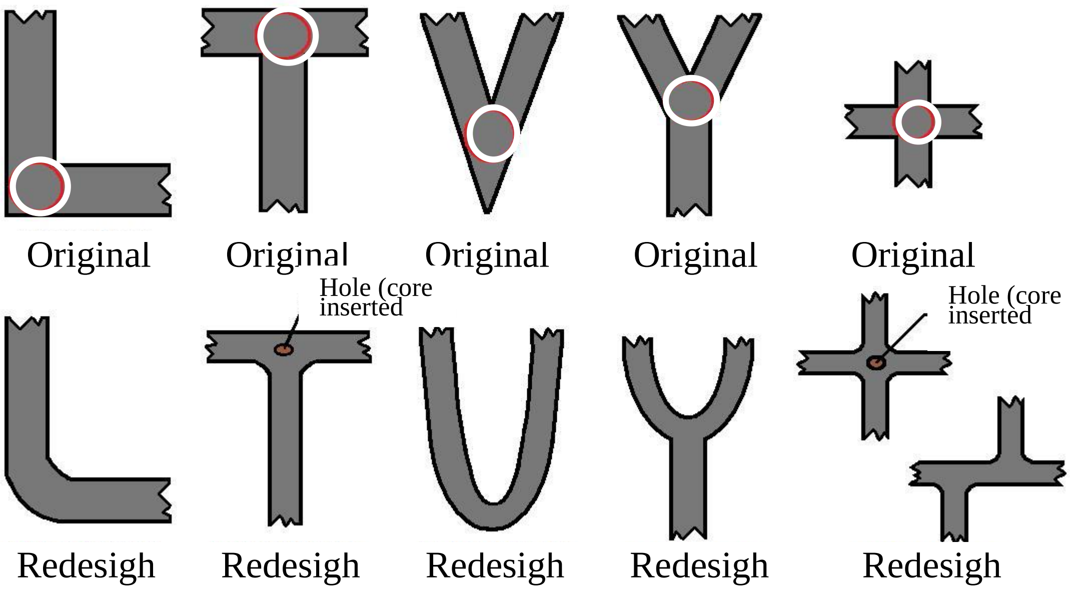


Figure 20 - Design of the metal casting

The flow of casting material must be carefully considered when manufacturing such junctions. If there is some flexibility in the design of the metal casting and it is possible you may want to think about redesigning the junction.

Prevent planes of weakness.

When metal castings solidify, columnar grain structures tend to develop, in the material, pointing towards the center. Due to this nature, sharp corners in the casting may develop a plane of weakness. By rounding the edges of sharp corners this can be prevented.

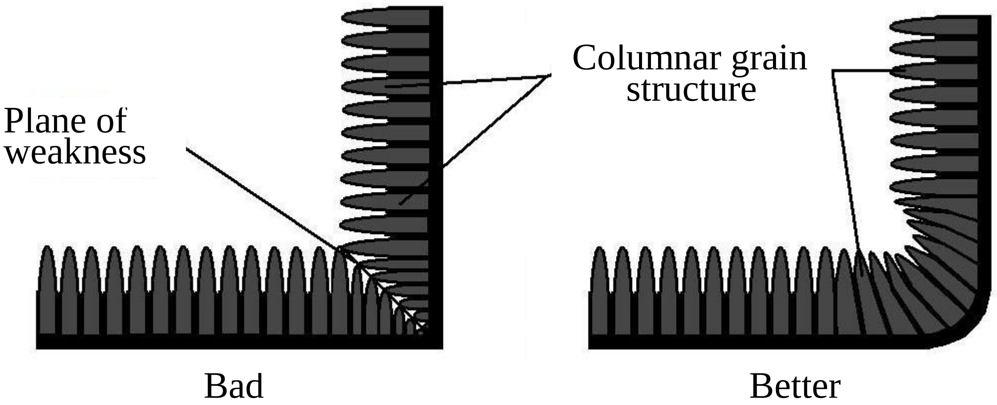


Figure 21 - Sharp corners in the casting

Reduce turbulence.

When manufacturing a metal casting, turbulence is always a factor in our flow of molten metal. Turbulence, as covered earlier in the pouring section, is bad because it can trap gases in the casting material and cause mold erosion. Although not altogether preventable in the manufacturing process, turbulence can be reduced by the design of a gating system that promotes a more laminar flow of the liquid metal. Sharp corners and abrupt changes in sections within the metal casting can be a leading cause of turbulence. Their affect can be mitigated by the employment of radii.

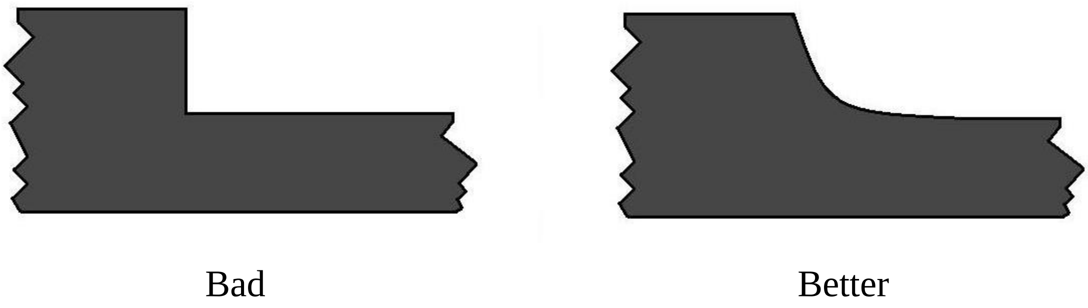


Figure 22 - Turbulences

Connection between riser and casting must stay open.

Riser design is very important in metal casting manufacture. If the passage linking the riser to the metal casting solidifies before the casting, the flow of molten metal to the casting will be blocked and the riser will cease to serve its function. If the connection has a larger cross sectional area it will decrease its time to freeze.

Good manufacturing design, however, dictates that that we minimize this cross section as much as possible to reduce the waste of material in the casting process. By making the passageway short we can keep the metal in its liquid state longer since it will be receiving more heat transfer from both the riser and the casting.

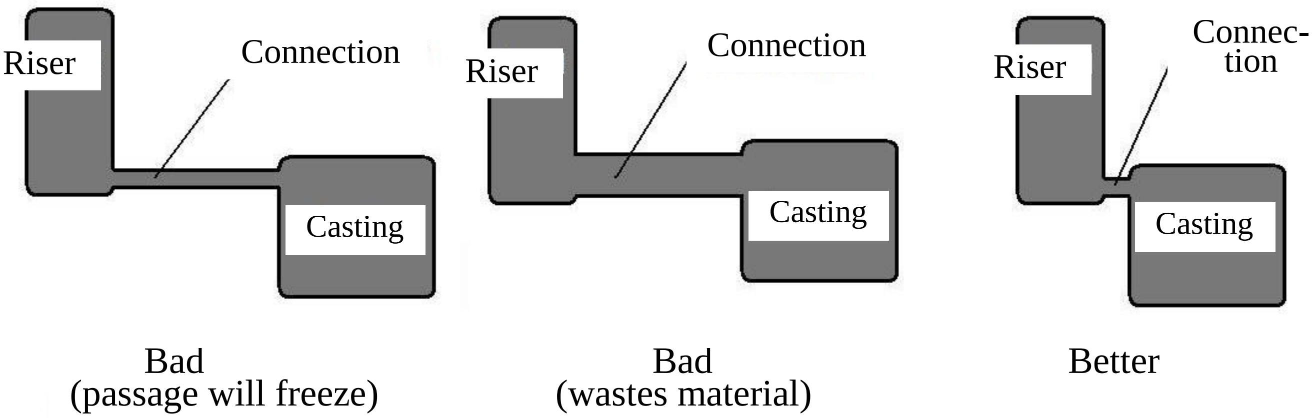


Figure 23 - Connection between riser and casting

Tapered down sprue.

Flow considerations for our metal casting manufacture begin as soon as the molten metal enters the mold. The liquid metal for the casting travels from the pouring basin through the down sprue, (Refer to Figure 8 in the Metal Casting Basics section). As it goes downward it will pick up speed, and thus it will have a tendency to separate from the walls of the mold. The down sprue must be tapered such that continuity of the fluid flow is maintained.

Remember the fluid mechanics equation for continuity $A_1V_1 = A_2V_2$.

Where V is the velocity of the liquid and A is the cross sectional area that it is traveling through. If you are casting for a hobby and/or just can not make these measurements, just remember it would be better to err on the side of making A_2 smaller, provided your pouring rate does not become too slow. In other words taper a little more and just adjust your pouring of the casting so that you keep a consistent flow of liquid metal.

Ingate design.

The ingate is another aspect of manufacturing design that relates to the flow of metal through the casting's system. The ingate, is basically where the casting material enters the actual mold cavity.

It is a crucial element, and all other factors of the metal casting's mold design are dependent on it. In the location next to the sprue base the cross sectional area of the ingate is reduced (choke area). The cross sectional reduction must be carefully calculated.

The flow rate of casting material into the mold can be controlled accurately in this way. The flow rate of the casting metal must be high enough to avoid any premature solidification.

However, you want to be certain that the flow of molten material into the mold does not exceed the rate of delivery into the pouring basin and thus ensure that the casting's gating system stays full of metal throughout the manufacturing process.

Other flow considerations.

In the manufacturing design phase, when planning the metal casting process, the analysis of the path of flow of liquid metal within the mold must be carefully calculated. At no point in the filling of the casting cavity should two separate streams of liquid metal meet. The result could be an incomplete fusion of the casting material (cold shut), as covered in the defects section under discontinuities.

Use of chills.

As mentioned earlier directional solidification is very important to the manufacture of a part during the metal casting process, in order to ensure that no area of the casting is cut off from the flow of liquid material before it solidifies. To achieve directional solidification within the metal casting, it is important to control the flow of fluid material and the solidification rate of the different areas of the metal casting. With respect to the solidification of the metal casting's different sections, regulation of thermal gradients is the key.

Sometimes we may have an area of the metal casting that will need to solidify at a faster rate in order to ensure that directional solidification occurs properly. Manufacture planning, and design of flow and section locations within the mold may not be sufficient.

To accelerate the solidification of a section like this in our casting, we may employ the use of chills. Chills act as heat sinks, increasing the cooling rate in the vicinity where they are placed.

Chills are solid geometric shapes of material, manufactured for this purpose. They are placed inside the mold cavity before pouring. Chills are of two basic types. Internal chills are located inside the mold cavity and are usually made of the same material as the casting. When the metal solidifies the internal chills are fused into the metal casting itself. External chills are located just outside of the casting. External chills are made of a material that can remove heat from the metal casting faster than the surrounding mold material. Possible materials for external chills include iron, copper, and graphite. Figure 24 demonstrates the use of the two types of chills to solve the hot spot problem in a + and T junction.

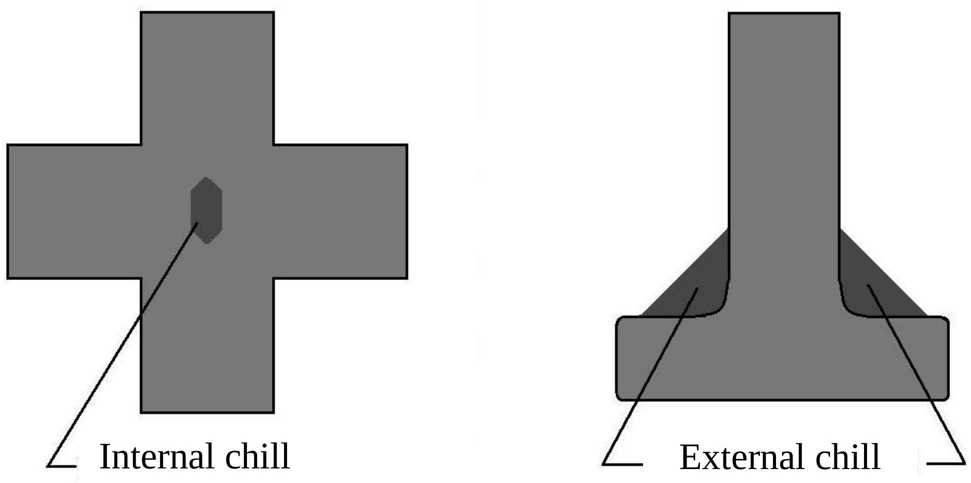


Figure 24 - Two types of chills

5. EXPENDABLE MOLD CASTUNG
5.1. Sand casting

Sand casting is the most widely used metal casting process in manufacturing. Almost all casting metals can be sand cast. Sand castings can range in size from very small to extremely large. Some examples of items manufactured in modern industry by sand casting processes are engine blocks, machine tool bases, cylinder heads, pump housings, and valves, just to name a few.

Sand. Product of the disintegration of rocks over long periods of time.

Most sand casting operations use silica sand (SiO_2). A great advantage of sand in manufacturing applications is that sand is inexpensive. Another advantage of sand to manufacture products by metal casting processes, is that sand is very resistant to elevated temperatures. In fact, sand casting is one of the few processes that can be used for metals with high melting temperatures such as steels, nickel, and titanium. Usually sand used to manufacture a mold for the casting process is held together by a mixture of water and clay.

A typical mixture by volume could be 89% sand, 4% water, 7% clay. Control of all aspects of the properties of sand is crucial when manufacturing parts by sand casting, therefore a sand laboratory is usually attached to the foundry.

Use of binder in sand casting.

A mold must have the physical integrity to keep its shape throughout the casting operation. For this reason, in sand casting, the sand must contain some type of binder that acts to hold the sand particles together. Clay serves an essential purpose in the sand casting manufacturing process, as a binding agent to adhere the molding sand together. In manufacturing industry other agents may be used to bond the molding sand together in place of clay. Organic resins, (such as phenolic resins), and inorganic bonding agents, (such as phosphate and sodium silicate), may also be used to hold the sand together.

In addition to sand and bonding agents, the sand mixture to create the metal casting mold will sometimes have other constituents added to it in order to improve mold properties.

Types of sand used in sand casting.

There are two general types of sand used in the manufacturing process of sand casting.

Naturally bonded- Naturally bonded sand is less expensive but it includes organic impurities that reduce the fusion temperature of the sand mixture for the casting, lower the binding strength, and require a higher moisture content.

Synthetic sand- Synthetic sand is mixed in a manufacturing lab starting with a pure (SiO_2) sand base. In this case, the composition can be controlled more accurately, which imparts the casting sand mixture with higher green strength, more permeability, and greater refractory strength. For these reasons, synthetic sand is mostly preferred in sand casting manufacture.

Properties of a sand casting mixture.

Type and content of binder and other additives.

As mentioned, controlling the type and content of the sand binder and other additives is the key to controlling the properties of the casting's mold sand mixture.

Moisture content.

Moisture content affects the other properties of the mixture such as strength and permeability. Too much moisture can cause steam bubbles to be entrapped in the metal casting.

Grain size.

This property represents the size of the individual particles of sand.

Shape of grains.

This property evaluates the shape of the individual grains of sand based on how round they are. Less round grains are said to be more irregular.

Strength.

The explanation of strength is, the ability of the sand casting mixture to hold its geometric shape under the conditions of mechanical stress imposed during the sand casting process.

Permeability.

The ability of the sand mold to permit the escape of air, gases, and steam during the sand casting process.

Collapsibility.

The ability of the sand mixture to collapse under force. Collapsibility is a very important property in this type of casting manufacture. Collapsibility of the mold will allow the metal casting to shrink freely during the solidification phase of the process. If the molding sand cannot collapse adequately for the casting's shrinkage, hot tearing or cracking will develop in the casting.

Flowability.

The ability of the sand mixture to flow over and fill the sand casting pattern during the impression making phase of the manufacturing process, more flowability is useful for a more detailed casting.

Refractory strength.

During the pouring of the molten metal in sand casting manufacture, the sand mixture in the mold must not melt, burn, crack, or sinter. The refractory strength is the ability of the mold sand mixture to withstand levels of extreme temperature.

Reusability.

The ability of the mold sand mixture to be reused to produce other sand castings in subsequent manufacturing operations.

When planning the manufacture of a particular casting, remember some properties of a sand casting mold mixture are contradictory to each other. Tradeoffs in different properties are often needed to achieve a compromise that provides a sand casting mold mixture with adequate properties for the specific part and casting application. There are some things to consider when selecting a sand mixture for a manufacturing process. Small grain size enhances mold strength, but large grain size is more permeable. Sand casting molds made from grains of irregular shape tend to be stronger because of grain interlocking, but rounder grains provide a better surface finish. A sand casting mold mixture with more collapsibility has less strength, and a sand casting mixture with more strength has less collapsibility.

Sand conditioning for a metal casting operation.

If the sand is being reused from a previous sand casting manufacturing process, lumps should be crushed and then all particles and metal granules removed, (a magnetic field may be used to assist in this). All sand and constituents should be screened. In industrial practice shakers, rotary screens, or vibrating screens, are used in this process. Then continuous screw-mixers or mulling machines are used to mix the sand uniformly.

Types of molds used in sand casting.

Green sand molds.

A green sand mold is very typical in sand casting manufacture, it is simple and easy to make, a mixture of sand, clay and water. The term green refers to the fact that the mold will contain moisture during the pouring of the casting.

Manufacturing considerations and properties of green sand molds:

1. Has sufficient strength for most sand casting applications.
2. Good collapsibility.
3. Good permeability.
4. Good reusability.
5. Least expensive of the molds used in sand casting manufacturing processes.
6. Moisture in sand can cause defects in some castings, dependent upon the type of metal used in the sand casting and the geometry of the part to be cast.

Dry sand molds.

Dry sand molds are baked in an oven, (at 300F - 650F for 8-48 hours), prior to the sand casting operation, in order to dry the mold. This drying strengthens the mold, and hardens its internal surfaces. Dry sand molds are manufactured using organic binders rather than clay.

Manufacturing considerations and properties of dry sand molds:

- Better dimensional accuracy of sand cast part than green sand molds.
- Better surface finish of sand cast part than green sand molds.

- More expensive manufacturing process than green sand production.
- Manufacturing production rate of castings are reduced due to drying time.
- Distortion of the mold is greater, (during mold manufacture).
- The metal casting is more susceptible to hot tearing because of the lower collapsibility of the mold.
- Dry sand casting is generally limited to the manufacture of medium and large castings.

Skin dried molds.

When sand casting a part by the skin dried mold process a green sand mold is employed, and its mold cavity surface is dried to a depth of .5 - 1 inch. Drying is a part of the manufacturing process and is accomplished by use of torches, heating lamps or some other means, such as drying it in air.

Manufacturing considerations and properties of skin dried molds:

- The cast part dimensional and surface finish advantages of dry sand molds are partially achieved.
- No large oven is needed.
- Special bonding materials must be added to the sand mixture to strengthen the mold cavity surface.

Cold setting processes.

In industrial sand casting manufacture, sometimes non-traditional binders other than those used in the above classifications of sand molds may be used. These binders may be made of a variety of things, such as synthetic liquid resins. Conventional casting binders require heat to cure while these when mixed with the sand, bond chemically at room temperature.

Hence the term cold setting processes. Technically advanced, these relatively recent sand casting processes are growing in manufacturing. While more expensive than green sand molds, cold setting processes provide good dimensional accuracy of the casting, and have high production applications.

Mold setup for sand casting.

The setup of a sand mold in manufacturing involves using a pattern to create an impression of the part to be sand cast within the mold, removal of the pattern, the placement of cores, (if needed), and the creation of a gating system within the mold. The setup of a mold is covered in detail in metal casting process. A mold setup such as the one in Figure 8 could be typical in a sand casting manufacturing operation.

The pattern.

A few different types of patterns may be used in the sand casting process.

Solid pattern.

This is a one piece pattern representing the geometry of the casting. It is an easy pattern to manufacture, but determining the parting line between cope and drag is more difficult for the foundry worker.

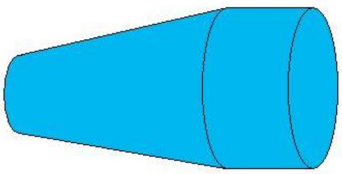


Figure 25 - Solid patten

Split pattern.

The split pattern is comprised of two separate parts that when put together will represent the geometry of the casting. When placed in the mold properly the plane at which the two parts are assembled should coincide with the parting line of the mold. This makes it easier to manufacture a pattern with more complicated geometry. Also mold setup is easier since the patterns placement relative to the parting line of the mold is predetermined.

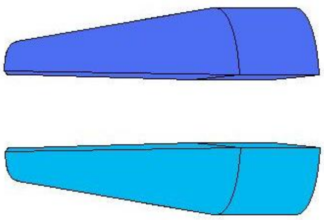


Figure 26 - Split pattern

Match plate pattern.

The match plate pattern is typically used in high production industry runs for sand casting manufacture. A match plate pattern is a two piece pattern representing the casting, divided at the parting line, similar to the split pattern. In the match plate pattern, however, each of the parts are mounted on a plate. The plates come together to assemble the pattern for the sand casting process. The match plate pattern is more proficient and makes alignment of the pattern in the mold quick and accurate.

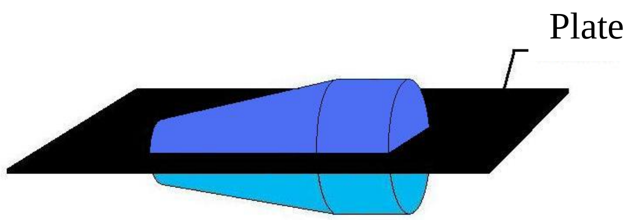


Figure 27 - Match plate pattern

Cope and drag pattern.

The cope and drag pattern is also typical in sand casting processes for high production industry runs. The cope and drag pattern is the same as the match plate pattern in that it is a two piece pattern representing the casting and divided at the parting line. Each of the two halves are mounted on a plate for easy alignment of the pattern and mold. The difference between the cope and drag pattern and the match plate pattern is that in the match plate pattern the two halves are mounted together, where as in the cope and drag pattern the two halves are separate. The cope and drag pattern enables the cope section of the mold, and the drag section of the mold to be created separately and latter assembled before the pouring of the sand casting.

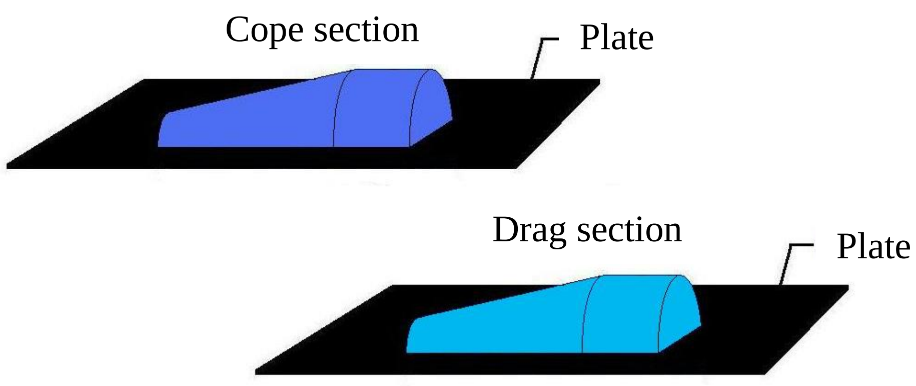


Figure 28 - Cope and drag pattern

In industrial sand casting processes a gating system, (not shown), is often incorporated as part of the pattern, particularly for a cope and drag pattern. Patterns can be made of different materials, and the geometry of the pattern must be adjusted for shrinkage, machine finish, and distortion. Pattern basics are covered in detail in the patterns section.

Cores.

Cores form the internal geometry of the casting. Cores are placed in the mold, and remain there during the pouring phase of the sand casting process. The metal casting will solidify around the core. Core basics are covered in detail in the cores section. Cores are made of the highest quality sand and are subject to extreme conditions during the sand casting operation. Cores must be strong and permeable; also, since the metal casting will shrink onto the core, cores must have sufficient collapsibility. Sometimes a reinforcing material will be placed in a sand casting core to enhance strength. The core may be manufactured with vents to facilitate the removal of gases.

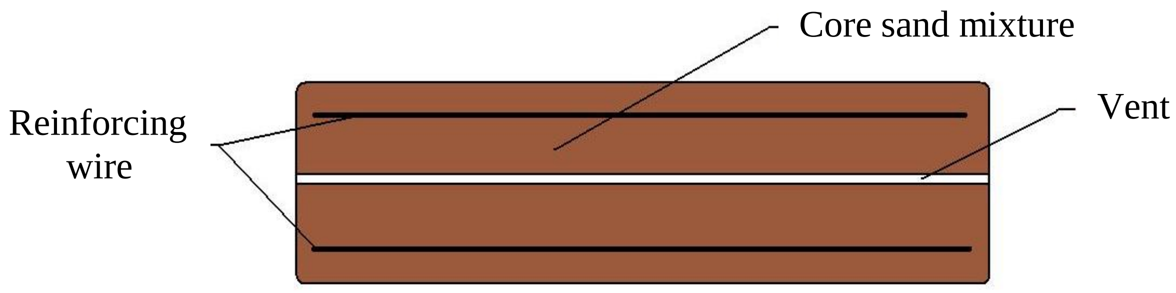


Figure 29 - Core

The sand casting operation.

The sand casting operation involves the pouring of the molten metal into the sand mold, the solidification of the casting within the mold, and the removal of the casting. The casting operation is covered in detail on the metal casting operation page.

Of specific interest to sand casting would be; the effect and dissipation of heat through the particular sand mold mixture during the casting's solidification, the effect of the flow of liquid metal on the integrity of the mold, (mold sand mixture properties and binder issues), and the escape of gases through the mixture. Sand usually has the ability to withstand extremely high temperature levels, and generally allows the escape of gases quite well.

Manufacturing with sand casting allows the creation of castings with complex geometry. Sand casting manufacture, however, only imparts a fair amount of dimensional accuracy to the cast part.

After the sand casting is removed from the sand mold it is shaken out, all the sand is otherwise removed from the casting, and the gating system is cut off the part. The part may then undergo further manufacturing processes such as heat treatment, machining, and/or metal forming. Inspection is always carried out on the finished part to evaluate the effectiveness and satisfaction of its manufacture.

5.2. Plaster mold casting

Plaster mold casting is a manufacturing process having a similar technique to sand casting. Plaster of Paris is used to form the mold for the casting, instead of sand. In industry parts such as valves, tooling, gears, and lock components may be manufactured by plaster mold casting.

The process.

Initially plaster of Paris is mixed with water just like in the first step of the formation of any plaster part. In the next step of the manufacture of a plaster casting mold, the plaster of Paris and water are then mixed with various additives such as talc and silica flour. The additives serve to control the setting time of the plaster and improve its strength.

The plaster of Paris mixture is then poured over the casting pattern. The slurry must sit for about 20 minutes before it sets enough to remove the pattern. The pattern used for this type of metal casting manufacture should be made from plastic or metal. Since it will experience prolonged exposure to water from the plaster mix, wood casting patterns have a tendency to warp.

After striping the pattern, the mold must be baked for several hours, to remove the moisture and become hard enough to pour the metal casting. The two halves of the mold are then assembled for the casting process. Castings of high detail and section thickness as low as 0,04 -1 inch, (2,5 - 1 mm), are possible when manufacturing by plaster mold casting.

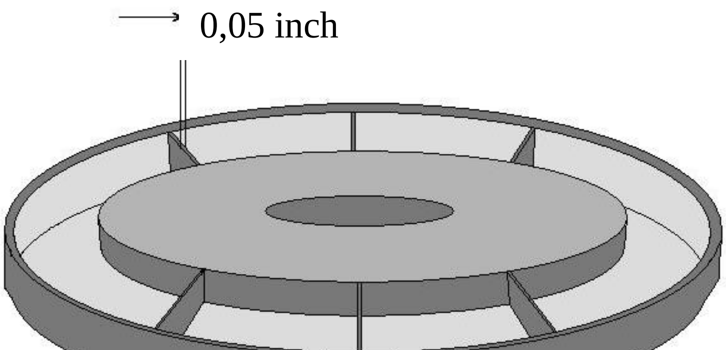


Figure 30 - Castings of high detail and section

Properties and considerations of manufacturing by plaster mold casting:

- When baking the casting mold just the right amount of water should be left in the mold material. Too much moisture in the mold can cause metal casting defects, but if the mold is too dehydrated, it will lack adequate strength.

- The fluid plaster slurry flows readily over the pattern, making an impression of great detail and surface finish. Also due to the low thermal conductivity of the mold material the casting will solidify slowly creating more uniform grain structure and mitigating casting warping. The qualities of the plaster mold enable the process to manufacture parts with excellent surface finish, thin sections, and produces high geometric accuracy.
- There is a limit to the casting materials that may be used for this type of manufacturing process, due to the fact that a plaster mold will not withstand temperature above 2200F (1200C). Higher melting point metals can not be cast in plaster. This process is typically used in industry to manufacture castings made from aluminum, magnesium, zinc, and copper based alloys.
- Manufacturing production rates for this type of metal casting process are relatively slow, due to the long preparation time of the mold.
- The plaster mold is not permeable, which severely limits the escape of gases from the casting.

Solving the permeability problem.

When manufacturing a metal casting by the plaster mold casting process one of the biggest problems facing a foundry man is the lack of permeability of the plaster mold.

Different techniques may be used in order to overcome this problem. The metal casting may be poured in a vacuum, or pressure may be used to evacuate the mold cavity just before pouring.

Another technique would be to produce permeability in the mold material by aerating the plaster slurry before forming the mold for the casting. This "foamed plaster" will allow for the much easier escape of gases from the casting. Sometimes in manufacturing industry a special technique called the Antioch Process may be used to make a permeable plaster metal casting mold.

The antioch process.

In the Antioch Process 50% plaster of Paris and 50% sand is mixed with water. The mixture is poured over the casting pattern and let set. After the pattern is removed, the mold is autoclaved in steam, (placed in an oven that uses hot steam under high pressure), and then let set in air. The resulting mold will easily allow the escape of gases from the casting.

5.3. Ceramic mold casting

The manufacturing process of ceramic mold casting is like the process of plaster mold casting but can cast materials at much higher temperatures. Instead of using plaster to create the mold for the metal casting, ceramic casting uses refractory ceramics for a mold material. In industry, parts such as machining cutters, dies for metalworking, metal molds, and impellers may be manufactured by this process.

The process.

The first step in manufacture by ceramic mold casting is to combine the material for the mold. A mixture of fine grain zircon ($ZrSiO_4$), aluminum oxide, fused silica, bonding agents, and water, creates a ceramic slurry. This slurry is poured over the casting pattern and let set. The pattern is then removed and the mold is left to dry. The mold is then fired.

The firing will burn off any unwanted material and make the mold hardened and rigid. The mold may also need to be baked in a furnace as well. The firing of the mold produces a network of microscopic cracks in the mold material. These cracks give the ceramic mold both good permeability and collapsibility for the metal casting process.

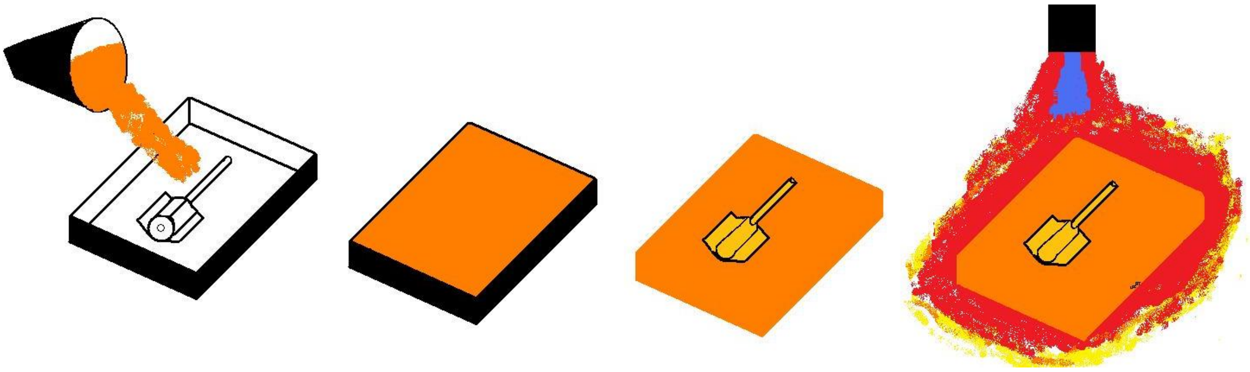


Figure 31 - The process of ceramic mold casting

Once prepared, the two halves of the mold are assembled for the pouring of the metal casting. The two halves, (cope and drag section), may be backed up with fireclay material for additional mold strength. Often in manufacturing industry, the ceramic mold will be preheated prior to pouring the molten metal. The metal casting is poured, and let solidify. In ceramic mold casting, like in other expendable mold processes, the ceramic mold is destroyed in the removal of the metal casting.

Properties and considerations of manufacturing by ceramic mold casting:

- Manufacturing by ceramic mold casting is similar to plaster mold casting in that it can produce parts with thin sections, excellent surface finish, and high dimensional accuracy. Manufacturing tolerances between .002 and .010 inches are possible with this process.
- To be able to cast parts with high dimensional accuracy eliminates the need for machining, and the scrap that would be produced by machining. Therefore, precision metal casting processes like this are efficient to cast precious metals, or materials that would be difficult to machine.
- Unlike the mold material in the plaster metal casting process, the refractory mold material in ceramic casting can withstand extremely elevated temperatures. Due to this heat tolerance, the ceramic casting process can be used to manufacture ferrous and other high melting point metal casting materials. Stainless steels and tool steels can be cast with this process.
- Ceramic mold casting is relatively expensive.
- The long preparation time of the mold makes manufacturing production rates for this process slow.
- Unlike in plaster mold casting, the ceramic mold has excellent permeability due to the microcrazing, (production of microscopic cracks), that occurs in the firing of the ceramic mold.

5.4. Shell molding

Shell mold casting or shell molding is a metal casting process in manufacturing industry in which the mold is a thin hardened shell of sand and thermosetting resin binder, backed up by some other material.

Shell molding was developed as a manufacturing process during the mid-20th century in Germany. Shell mold casting is particularly suitable for steel castings under 20 lbs; however almost any metal that can be cast in sand can be cast with the shell molding process. Also much larger parts have been manufactured with shell molding. Typical parts manufactured in industry using the shell mold casting process include cylinder heads, gears, bushings, connecting rods, camshafts and valve bodies.

The process.

The first step in the shell mold casting process is to manufacture the shell mold. The sand we use for the shell molding process is of a much smaller grain size than the typical green sand mold. This fine grained sand is mixed with a thermosetting resin binder. A special metal pattern is coated with a parting agent, (typically silicone), which will latter facilitate in the removal of the shell. The metal pattern is then heated to a temperature of 350F-700F degrees, (175C-370C).

The sand mixture is then poured or blown over the hot casting pattern. Due to the reaction of the thermosetting resin with the hot metal pattern, a thin shell forms on the surface of the pattern.

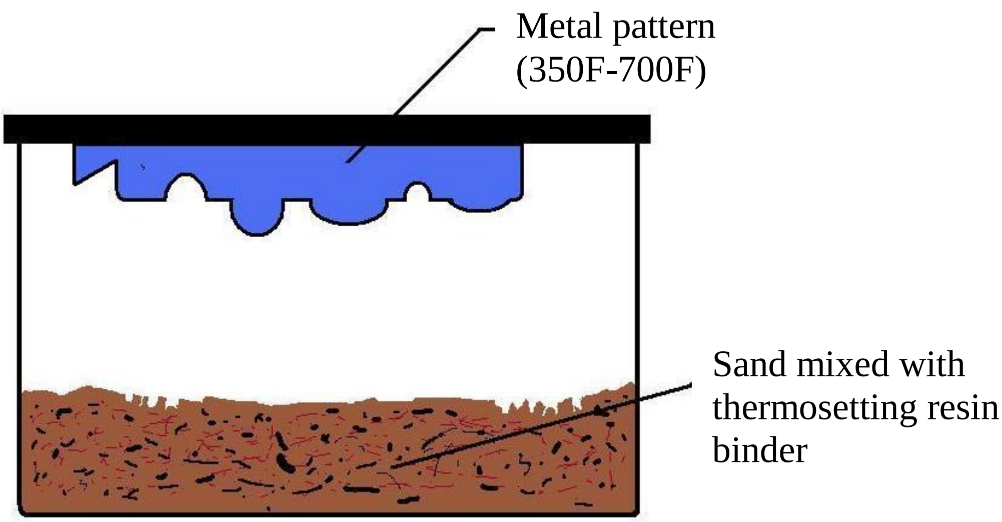


Figure 32 - The first step in the shell mold casting process

The desired thickness of the shell is dependent upon the strength requirements of the mold for the particular metal casting application. A typical industrial manufacturing mold for a shell molding casting process could be 0,3 inch (7,5mm) thick. The thickness of the mold can be controlled by the length of time the sand mixture is in contact with the metal casting pattern.

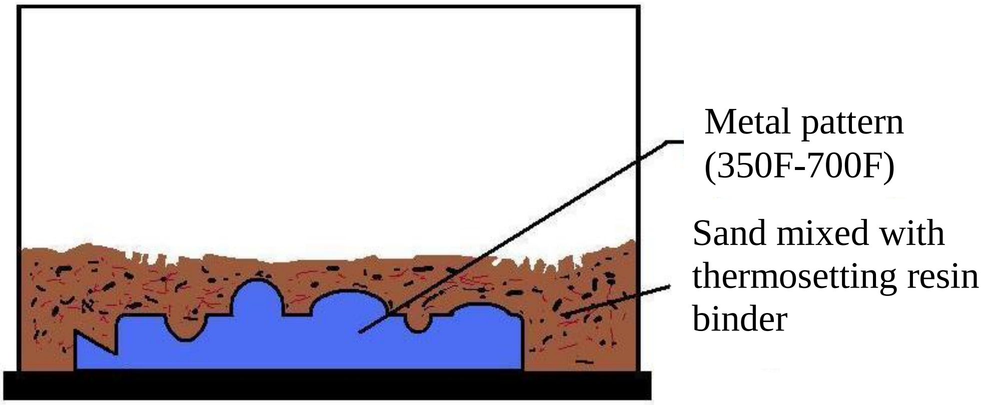


Figure 33 - The second step in the shell mold casting process

The excess "loose" sand is then removed, leaving the shell and pattern.

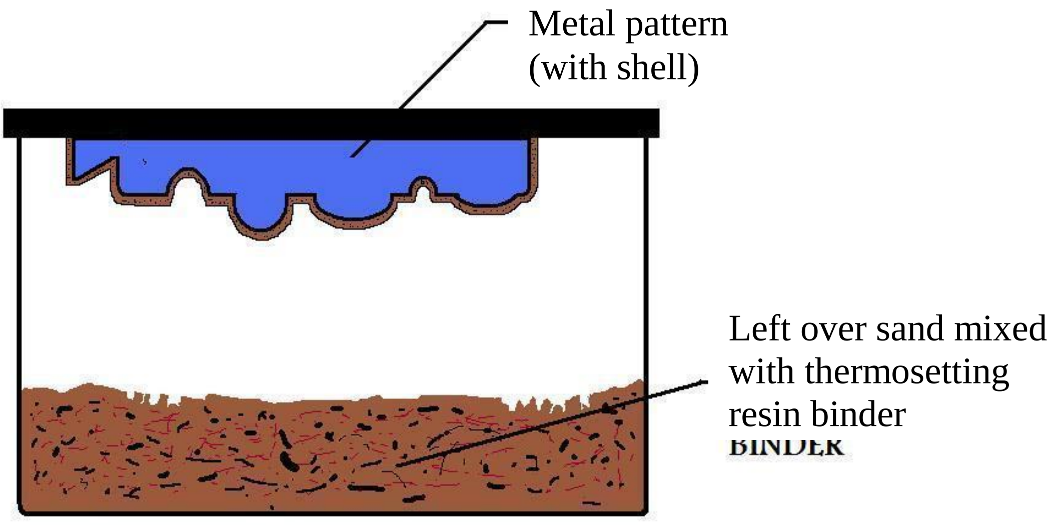


Figure 34 - The third step in the shell mold casting process

The shell and pattern are then placed in an oven for a short period of time, (minutes), which causes the shell to harden onto the casting pattern.

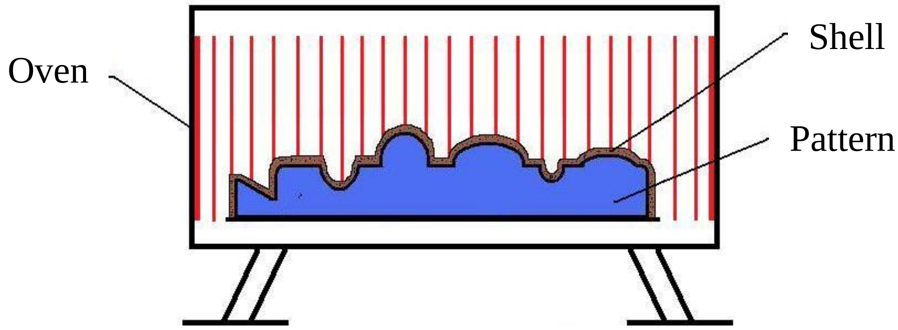


Figure 35 - Shell and pattern are baked in oven to harden shell mold

Once the baking phase of the manufacturing process is complete, the hardened shell is separated from the casting pattern by way of ejector pins built into the pattern. This manufacturing technique used to create the mold in the shell molding process can also be employed to produced highly accurate fine grained mold cores for other metal casting processes.

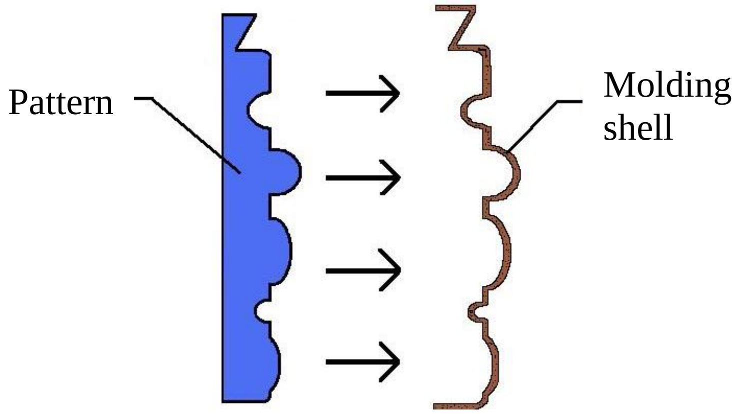


Figure 36 - The hardened shell is separated from the casting pattern

Two of these hardened shells, each representing half the mold for the casting, are assembled together either by gluing or clamping.

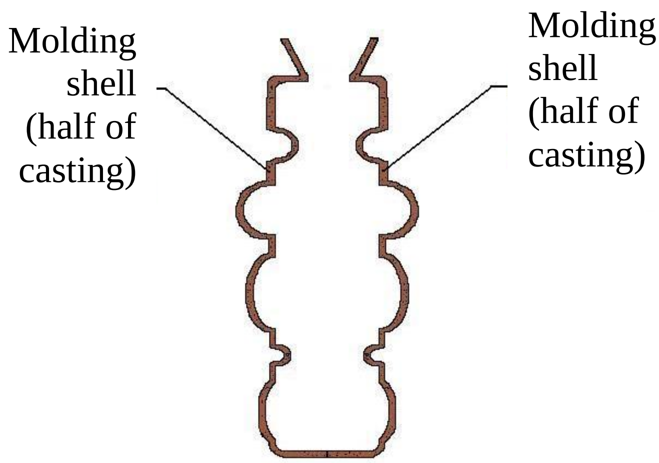


Figure 37 - Assembling of two hardened shells

The manufacture of the shell mold is now complete and ready for the pouring of the metal casting. In many shell molding processes, the shell mold is supported by sand or metal shot during the casting process.

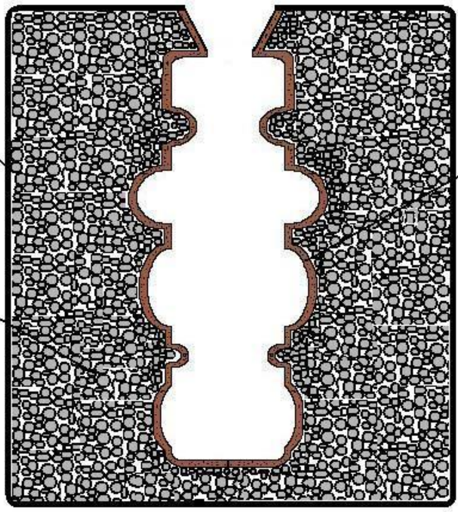


Figure 38 - The completed shell mold

Properties and considerations of manufacturing by shell mold casting:

- The internal surface of the shell mold is very smooth and rigid. This allows for an easy flow of the liquid metal through the mold cavity during the pouring of the casting, giving castings a very good surface finish. Shell mold casting enables the manufacture of complex parts with thin sections and smaller projections than green sand mold casting.
- Manufacturing with the shell mold process also imparts high dimensional accuracy. Tolerances of 0,010 inches (0,25mm) are possible. Further machining is usually unnecessary when casting by this process.
- Shell sand molds are less permeable than green sand molds and binder may produce a large volume of gas as it contacts the molten metal being poured for the casting. For these reasons, shell molds should be well ventilated.
- The expense of shell mold casting is increased by the cost of the thermosetting resin binder, but decreased by the fact that only a small percentage of sand is used compared to other sand casting processes.
- Shell mold casting processes are easily automated.
- The special metal patterns needed for shell mold casting are expensive, making it a less desirable process for short runs. However, manufacturing by shell casting may be economical for large batch production.

5.5. Vacuum casting

Vacuum mold casting, also known in manufacturing industry as the V process, employs a sand mold that contains no moisture or binders. The internal cavity of the mold holds the shape of the casting due to forces exerted by the pressure of a vacuum. Vacuum molding is a casting process that was developed in Japan around 1970.

The process.

A special pattern is used for the vacuum mold casting process. It is either a match-plate or a cope and drag pattern with tiny holes to enable a vacuum suction. A thin plastic sheet is placed over the casting pattern and the vacuum pressure is turned on, causing the sheet to adhere to the surface of the pattern.

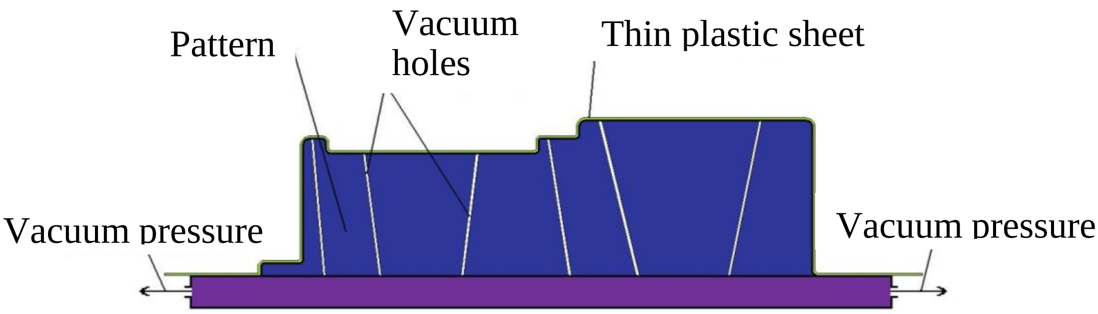


Figure 39 - Special pattern

A special flask is used for this manufacturing process. The flask has holes to utilize vacuum pressure. This flask is placed over the casting pattern and filled with sand.

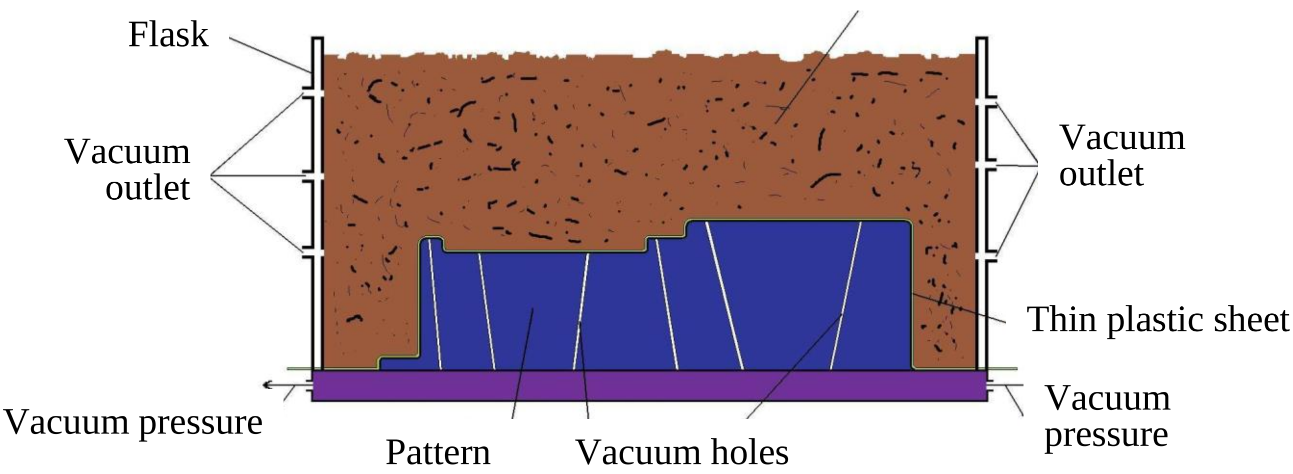


Figure 40 - Special flask

A pouring cup and sprue are cut into the mold for the pouring of the metal casting.

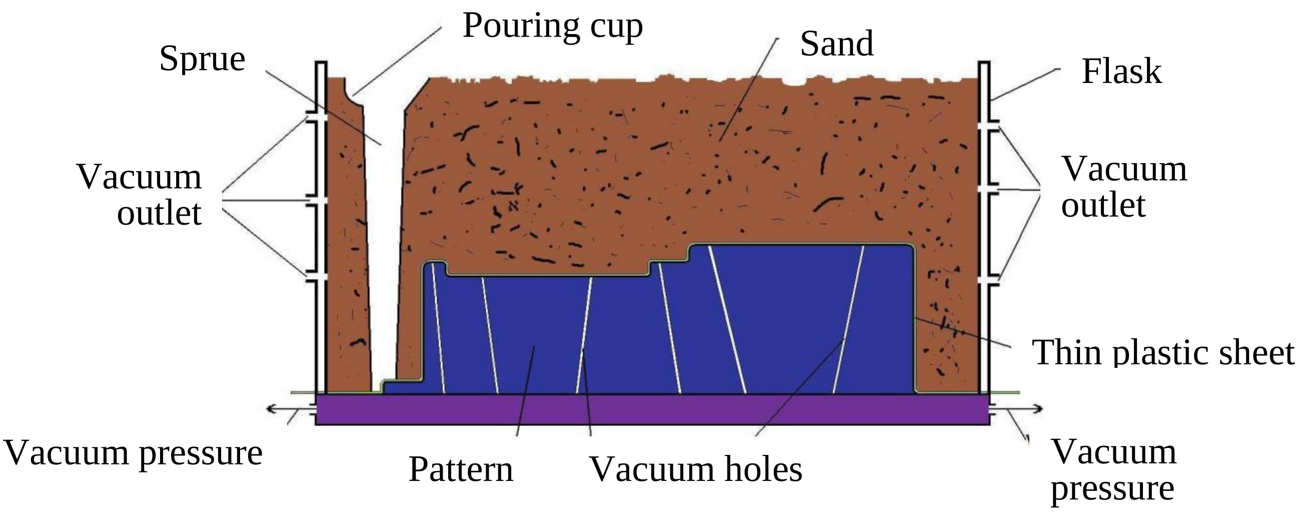


Figure 41 - Pouring cup and sprue

Next, another thin plastic sheet is placed over the top of the mold. The vacuum pressure acting through the flask is turned on, and the plastic film adheres to the top of the mold.

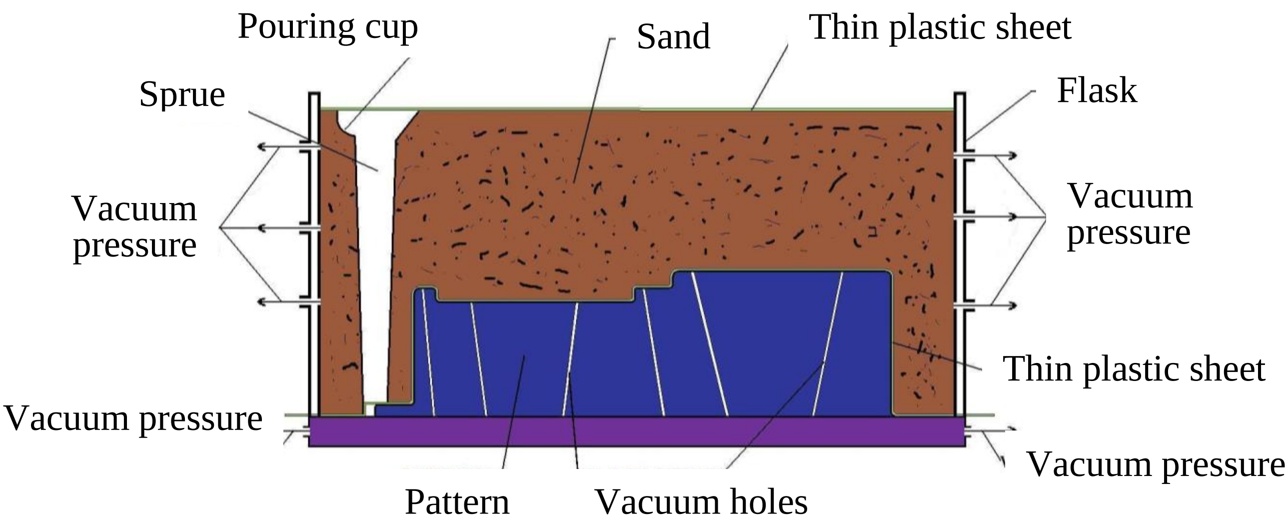


Figure 42 - Thin plastic sheets

In the next stage of vacuum mold casting manufacture, the vacuum on the special casting pattern is turned off and the pattern is removed. The vacuum pressure from the flask is still on. This causes the plastic film on the top to adhere to the top and the plastic film formerly on the pattern to adhere to the bottom. The film on the bottom is now holding the impression of the casting in the sand with the force of the vacuum suction.

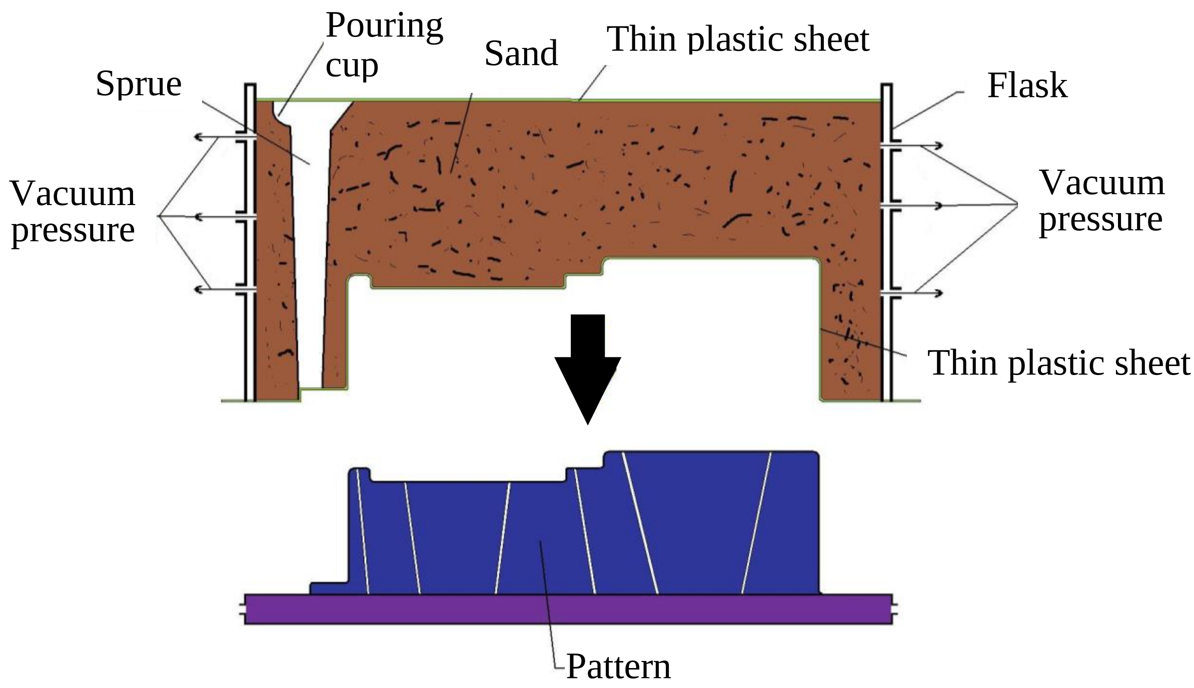


Figure 43 - Removing the pattern

The drag portion of the mold is manufactured in the same fashion. The two halves are then assembled for the pouring of the casting. Note that there are now 4 plastic films in use. One on each half of the internal casting cavity and one on each of the outer surfaces of the cope and drag.

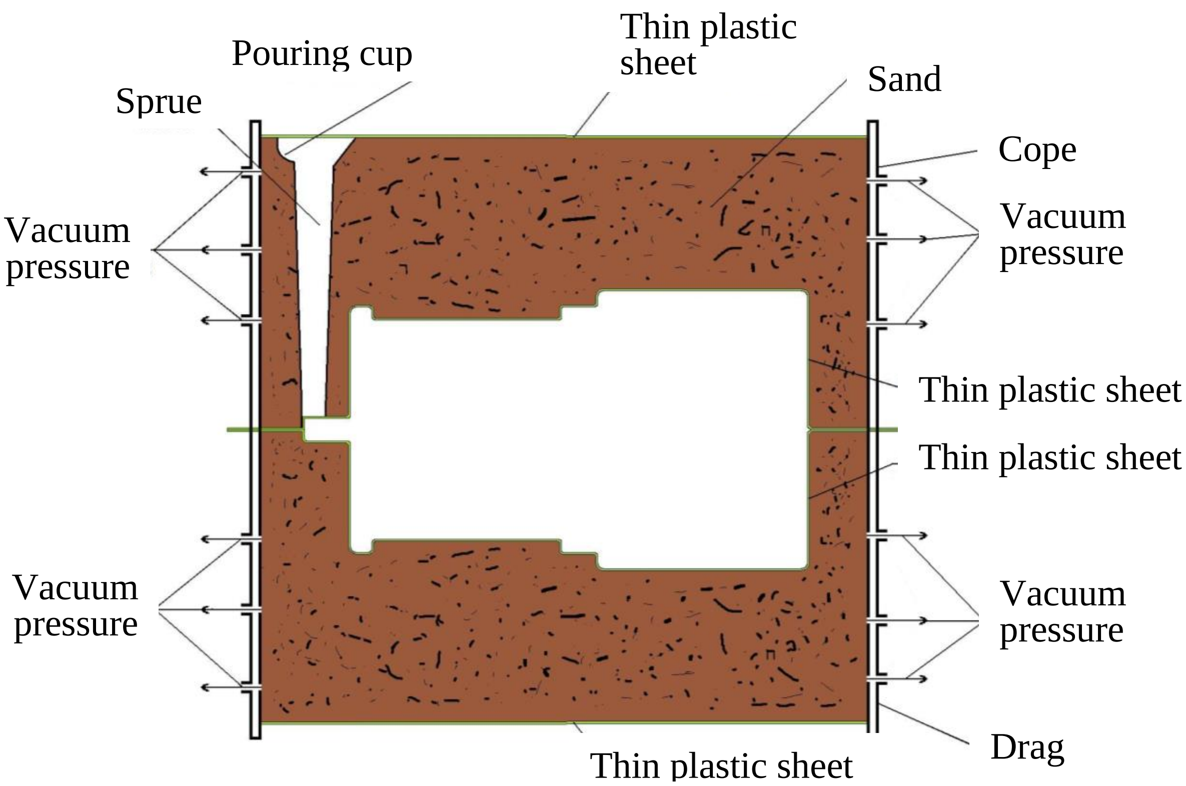


Figure 44 - The drag portion of the mold

During the pouring of the casting, the molten metal easily burns away the plastic.

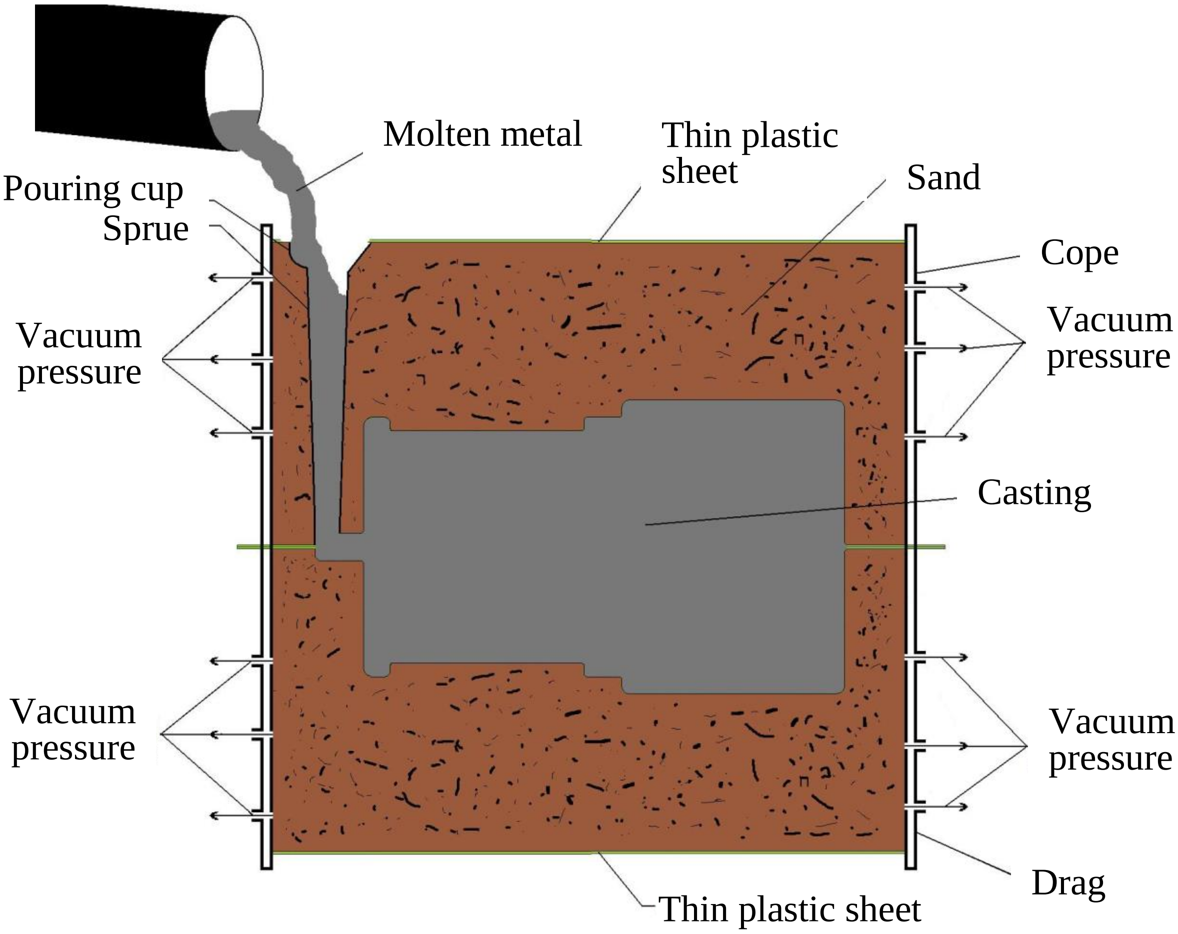


Figure 45 - Pouring of the casting

Properties and considerations of manufacturing by vacuum mold casting:

- In vacuum mold casting manufacture there is no need for special molding sands or binders.
- Sand recovery and reconditioning, a common problem in metal casting industry, is very easy due to the lack of binders and other agents in the sand.
- When manufacturing parts by vacuum mold casting the sand mold contains no water, so moisture related metal casting defects are eliminated.
- The size of risers can be significantly reduced for this metal casting process, making it more efficient in the use of material.
- Casting manufacture by vacuum molding is a relatively slow process.
- Vacuum mold casting is not well suited to automation.

5.6. Expanded polystyrene casting

In the expanded polystyrene casting process, a sand mold is packed around a polystyrene pattern representing the metal casting to be manufactured. The pattern is not removed, and the molten metal is poured into the pattern which is vaporized from the heat of the metal. The liquid metal takes the place of the vaporized polystyrene and the casting solidifies in the sand mold.

In metal casting industry this process is known as the lost-foam process, evaporative pattern casting, or the full mold process. A large variety of castings of different sizes and materials can be manufactured using this technique. Parts produced in manufacturing industry using this process include crankshafts, cylinder heads, machine bases, manifolds, and engine blocks.

The process.

The first step in the evaporative casting process is to manufacture the polystyrene pattern. For small production runs, a pattern may be cut from larger sections of polystyrene material and assembled together. For large industrial manufacturing processes, the pattern will be molded. A die, often made from aluminum, is used for this process. Polystyrene beads are placed in the die and heated, they expand from the heat and the foam material takes the shape of the die.

Depending upon the complexity of the casting, several of these polystyrene sections may have to be adhered together to form the pattern. In most cases the pattern is coated with a refractory compound, this will help create a good surface finish on the metal casting. In addition to the casting itself, the foam pattern will also include the pouring cup and gating system.

The pattern is then placed in a flask and molding sand is packed around it. The sand may or may not contain bonding agents, dependent upon the particular manufacturing procedure.

The molten metal is then poured into the mold without removing the pattern. The liquid metal vaporizes the polystyrene pattern, as it flows through the mold cavity. Any left over product from the vaporized polystyrene material is absorbed into the molding sand.

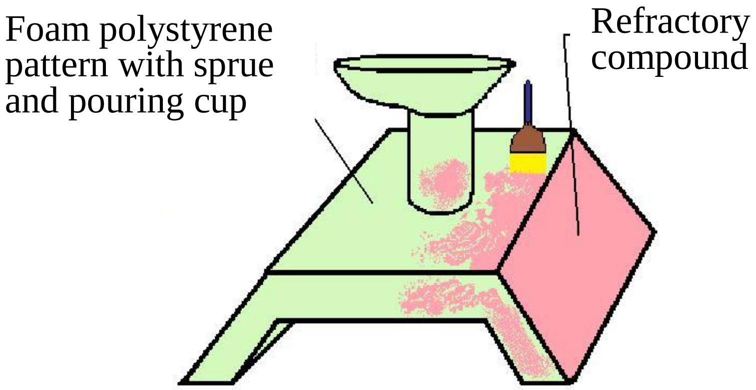


Figure 46 - The foam pattern

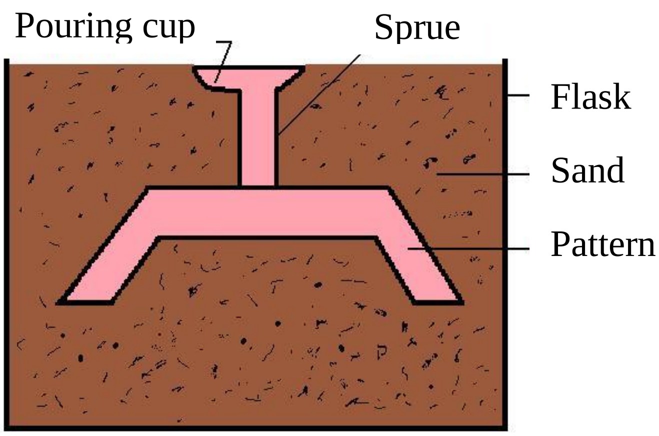


Figure 47 - Pattern is placed in a flask and molding sand

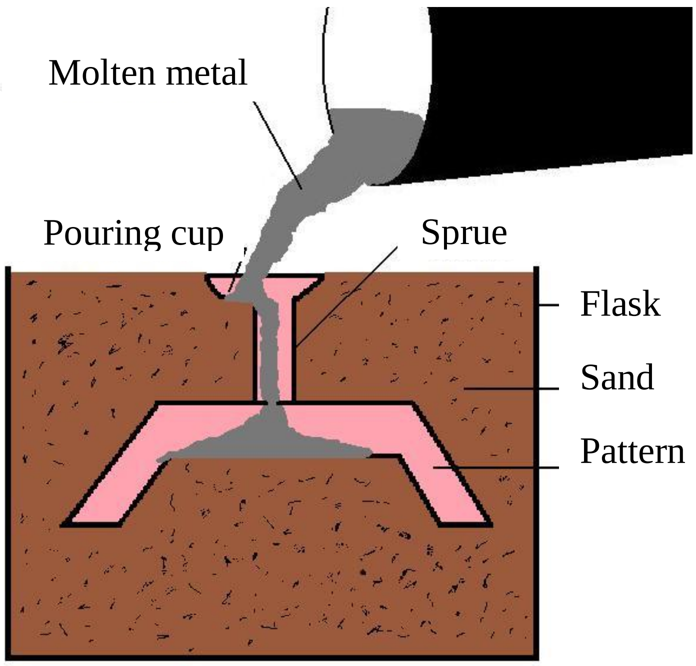


Figure 48 - Pouring of the expanded polystyrene casting

The molten metal is then allowed to harden within the sand mold. Once solidified, the casting is removed.

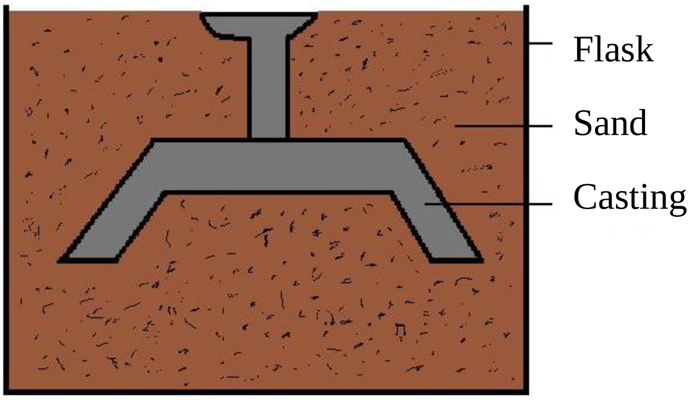


Figure 49 - Molten metal in the sand mold

Properties and considerations of manufacturing by expanded polystyrene casting:

- If a core is need it is incorporated within the pattern. Therefore placing and securing a core in the mold cavity before the pouring of the metal casting is not a step in this manufacturing process.
- Flasks for this process are simple and not expensive. Also the manufacturing process itself is easy, since there is no parting line or removal of the pattern needed.
- In manufacturing industry, patterns for expanded polystyrene metal casting will always include the full gating system.
- Due to the extra energy required to vaporize the polystyrene, there will be a large thermal gradient present at the metal-pattern interface as the casting is being poured.
- Very complex metal casting geometry can be produced using this process.
- This manufacturing process can be very efficient in the production of metal castings for large industrial runs. The main cost is to create the die to produce the foam polystyrene patterns. Once that is overcome, the process itself is very inexpensive.
- This manufacturing process can be easily automated.

5.7. Investment casting

Investment casting is a manufacturing process in which a wax pattern is coated with a refractory ceramic material. Once the ceramic material is hardened its internal geometry takes the shape of the casting.

The wax is melted out and molten metal is poured into the cavity where the wax pattern was. The metal solidifies within the ceramic mold and then the metal casting is broken out. This manufacturing technique is also known as the lost wax process. Investment casting was developed over 5500 years ago and can trace its roots back to both ancient Egypt and China. Parts manufactured in industry by this process include dental fixtures, gears, cams, ratchets, jewelry, turbine blades, machinery components and other parts of complex geometry.

The process.

The first step in investment casting is to manufacture the wax pattern for the process. The pattern for this process may also be made from plastic; however it is often made of wax since it will melt out easily and wax can be reused. Since the pattern is destroyed in the process, one will be needed for each casting to be made. When producing parts in any quantity, a mold from which to manufacture patterns will be desired. Similar to the mold that may be employed in the expanded polystyrene casting process to produce foam polystyrene patterns, the mold to create wax patterns may be cast or machined. The size of this master die must be carefully calculated. It must take into consideration shrinkage of wax, shrinkage of the ceramic material invested over the wax pattern and shrinkage of the metal casting. It may take some trial and error to get just the right size, therefore these molds can be expensive. Since the mold does not need to be opened, castings of very complex geometry can be manufactured. Several wax patterns may be combined for a single casting.

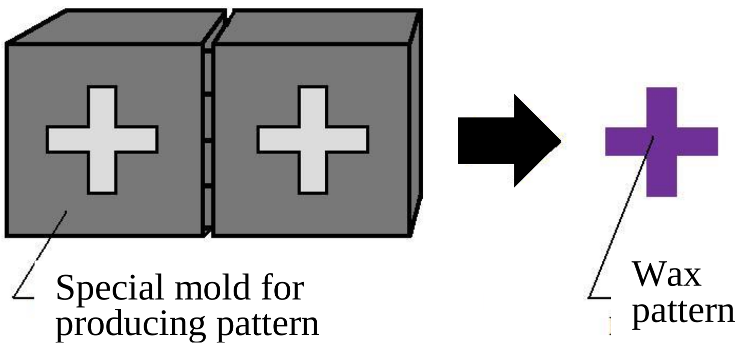


Figure 50 - Manufacture the pattern

Or as often the case, many wax patterns may be connected and poured together producing many castings in a single process. This is done by attaching the wax patterns to a wax bar, the bar serves as a central sprue. A ceramic pouring cup is attached to the end of the bar. This arrangement is called a tree, denoting the similarity of casting patterns on the central runner beam to branches on a tree.

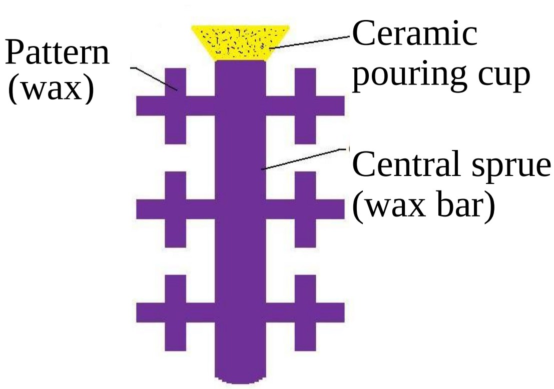


Figure 51 - Wax pattern tree for investment casting

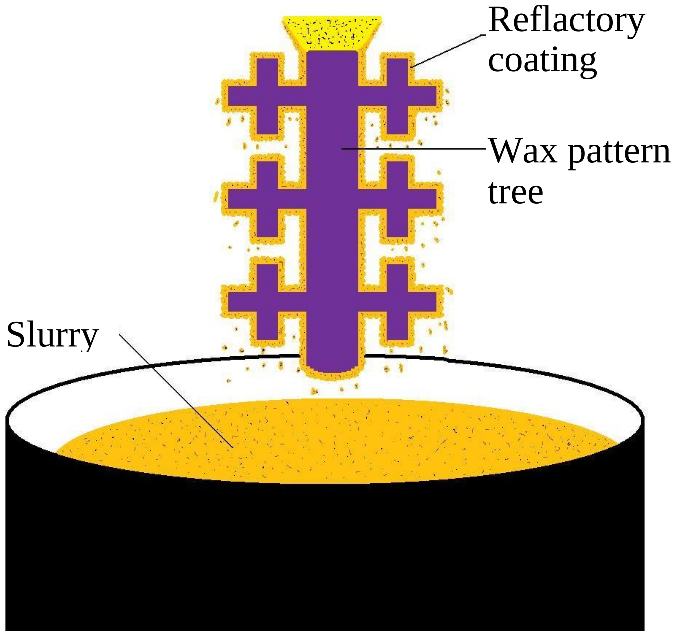


Figure 52 - Refractory slurry invested over wax pattern

The metal casting pattern is then dipped in a refractory slurry whose composition includes extremely fine grained silica, water and binders. A ceramic layer is obtained over the surface of the pattern. The pattern is then repeatedly dipped into the slurry to increase the thickness of the ceramic coat. In some cases the pattern may be placed in a flask and the ceramic slurry poured over it. Once the refractory coat over the pattern is thick enough, it is allowed to dry in air in order to harden.

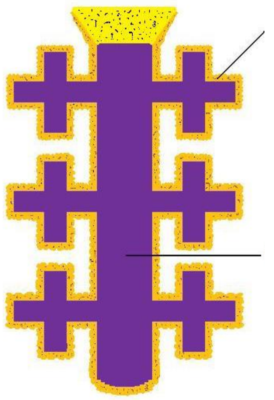


Figure 53 - Refractory slurry invested over wax pattern drying in air

The next step in this manufacturing process is the key to investment casting. The hardened ceramic mold is turned upside down and heated to a temperature of around 200F-375F (90°C-175 °C). This causes the wax to flow out of the mold, leaving the cavity for the metal casting.

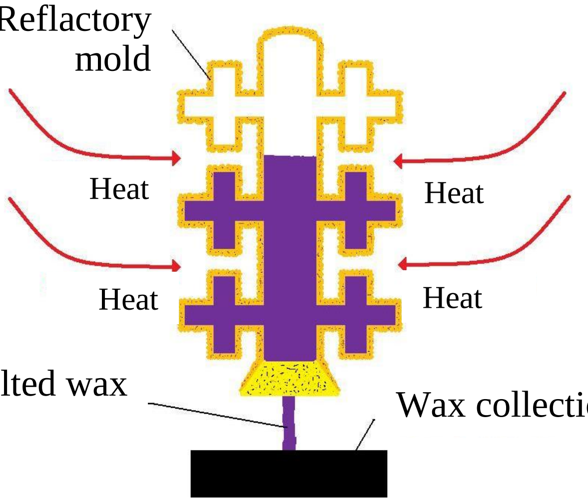


Figure 54 - Wax melted out of mold for investment casting

The ceramic mold is then heated to around 1000F-2000F (550°C-1100°C). This will further strengthen the mold, eliminate any leftover wax or contaminants and drive out water from the mold material. The metal casting is then poured while the mold is still hot. Pouring the casting while the mold is hot allows the liquid metal to flow easily through the mold cavity, filling detailed and thin sections. Pouring the metal casting in a hot mold also gives better dimensional accuracy, since the mold and casting will shrink together as they cool.

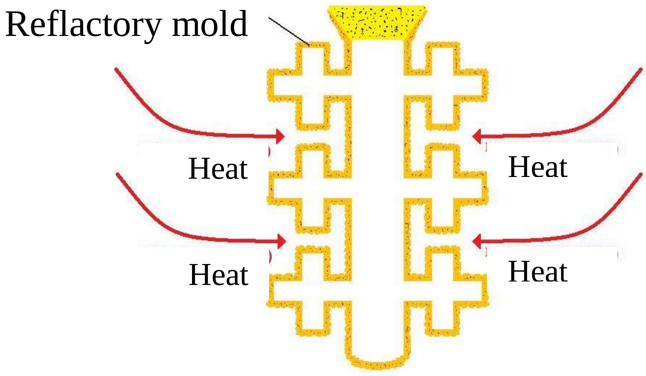


Figure 55 - Mold for investment casting heated before pouring

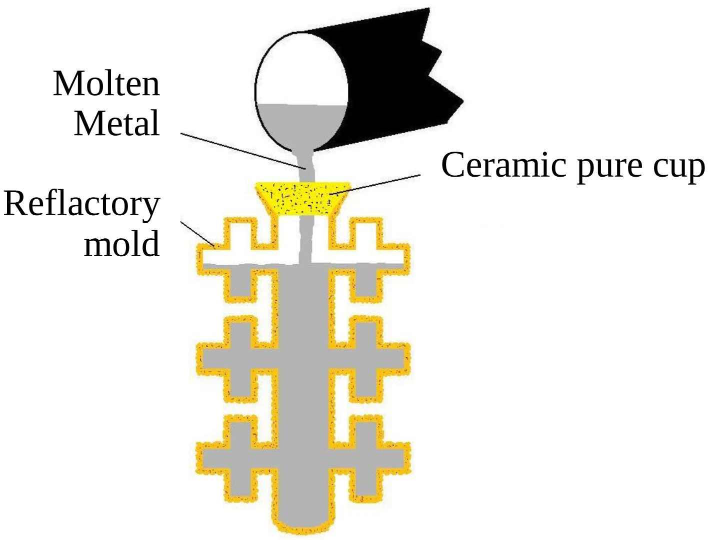


Figure 56 - Pouring of an investment casting

After pouring of the molten metal into the mold, the casting is allowed to set as the solidification process takes place.

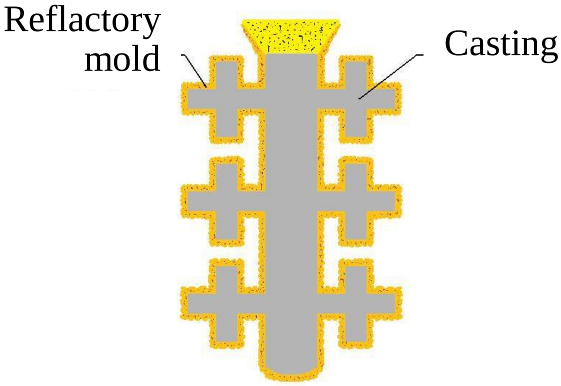


Figure 57 - Solidification of an investment casting

The final step in this manufacturing process involves breaking the ceramic mold from the investment casting and cutting the parts from the tree.

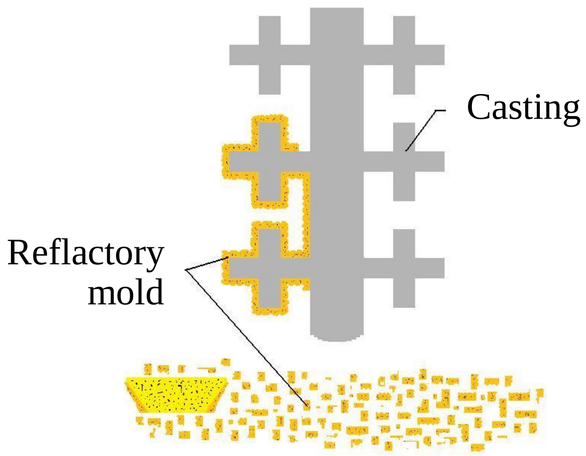


Figure 58 - Break up of the mold for investment casting

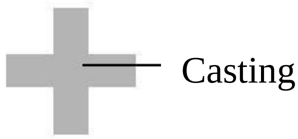


Figure 59 - Investment casting final product

Properties and considerations of manufacturing by investment casting:

- Investment casting is a manufacturing process that allows the casting of extremely complex parts, with good surface finish.
- Very thin sections can be produced by this process. Metal castings with sections ~ .015in (.4mm) have been manufactured using investment casting.
- Investment casting also allows for high dimensional accuracy. Tolerances as low as 0,003 in (0,076 mm) have been claimed.
- Practically any metal can be investment cast. Parts manufactured by this process are generally small, but parts weighing up to 75 lbs have been found suitable for this technique.
- Parts of the investment process may be automated.
- Investment casting is a complicated process and is relatively expensive.

6. PERMANENT MOLD CASTING
6.1. Basic permanent mold casting

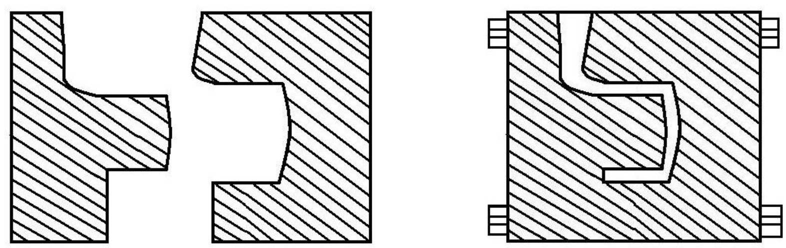
Basic permanent mold casting is a generic term used to describe all permanent mold casting processes. The main similarity of this group being the employment of a permanent mold that can be used repeatedly for multiple metal castings. The mold also called a die, is commonly made of steel or iron, but other metals or ceramics can be used. Parts that may be manufactured in industry using this metal casting process include cylinder blocks, cylinder heads, pistons, connecting rods, parts for aircraft and rockets, gear blanks and kitchenware.

The process.

When planning to manufacture using a permanent mold manufacturing process the first step is to create the mold. The sections of the mold are most likely machined from two separate metal blocks. These parts are manufactured precisely. They are created so that they fit together and may be opened and closed easily and accurately. The gating system as well as the part geometry is machined into the casting mold.

A significant amount of resources need to be utilized in the production of the mold, making setup more expensive for permanent mold manufacturing runs. However, once created, a permanent mold may be used tens of thousands of times before its mold life is up. Due to the continuous repetition of high forces and temperatures, all molds will eventually decay to the point where they can no longer effectively manufacture quality metal castings.

The number of castings produced by that particular mold before it had to be replaced is termed mold life. Many factors affect mold life such as the molds operating temperature, mold material and casting metal.



Two halves of a basic permanent mold (cross-sectional)

Basic permanent mold assembled (cross-sectional)

Figure 60 - Basic permanent mold

Before pouring the metal casting, the internal surfaces of the permanent mold are sprayed with a slurry consisting of refractory materials suspended in liquid. This coating serves as a thermal gradient, helping to control the heat flow and acting as a lubricant for easier removal of the cast part. In addition, applying the refractory coat as a regular part of the manufacturing process will increase the mold life of the valuable mold.

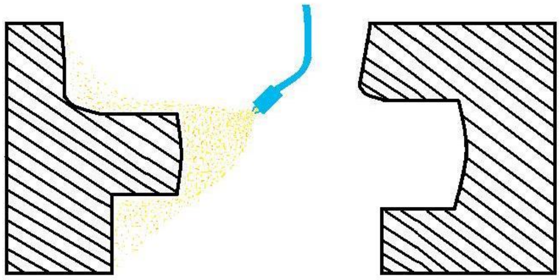


Figure 61 - Basic permanent mold being sprayed with refractory slurry prior to the casting operation

The two parts of the mold must be closed and held together with force, using some sort of mechanical means. Most likely, the mold will be heated prior to the pouring of the metal casting. A possible temperature that a permanent metal casting mold may be heated to before pouring could be around 350F (175C). The heating of the mold will facilitate the smoother flow of the liquid metal through the mold's gating system and casting cavity. Pouring in a heated mold will also reduce the thermal shock encountered by the mold due to the high temperature gradient between the molten metal and the mold. This will act to increase mold life. Once securely closed and heated, the permanent mold is ready for the pouring of the cast part.

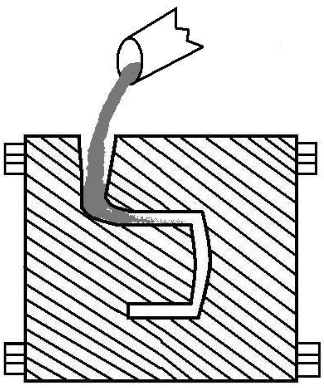


Figure 62 - Pouring of basic permanent mold (gravity fed process)

After pouring, the metal casting solidifies within the mold.

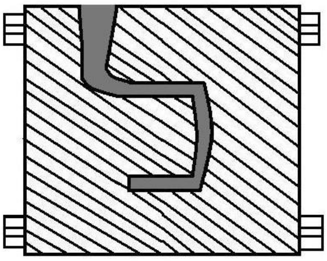


Figure 63 - Solidification of casting in basic permanent mold

In manufacturing practice, the metal cast part is usually removed before much cooling occurs, to prevent the solid metal casting from contracting too much in the mold. This is done to prevent cracking the casting, since the permanent mold does not collapse. The removal of the part is accomplished by way of ejector pins built into the mold.

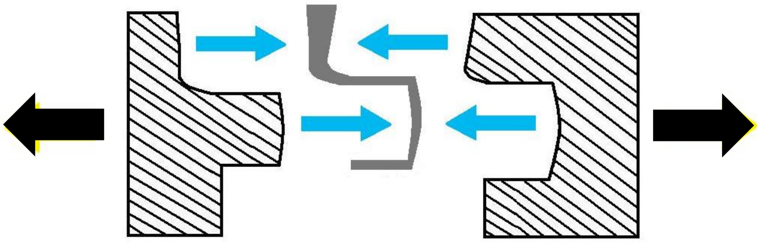


Figure 64 - Basic permanent mold is open and solidified casting is ejected

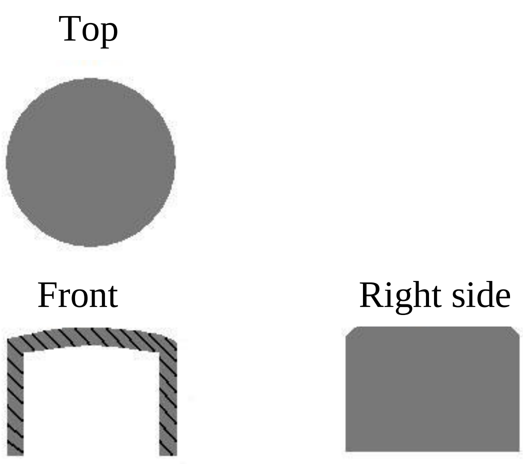


Figure 65 - Views of metal casting produced (piston)

Semipermanent mold casting.

Cores are often employed in a permanent mold metal casting process. These cores are likely made of the same material of the mold and are also permanent. The geometry of the these cores has to allow for the removal of the casting or the cores need to be able to collapse by some mechanical means. Sand cores have a lot less limitations and can be used in conjunction with permanent molds. Sand cores are placed within the permanent mold prior to pouring the metal casting. The sand cores are not permanent, like the mold and must be broken up and replaced with every casting. Sand cores, however, allow for more freedom in the manufacture of internal geometry. In manufacturing industry using a disposable core with a permanent mold is called semipermanent mold casting.

Properties and considerations of manufacturing by basic permanent mold casting:

- Generally this manufacturing process is only suited for materials with lower melting temperatures, such as zinc, copper, magnesium and aluminum alloys.
- Cast iron parts are also manufactured by this process but the high melting temperature of cast iron is hard on the mold.
- Steels may be cast in permanent molds made of graphite or some special refractory material.
- The mold may be cooled by water or heat fins to help with the dissipation of heat during the metal casting process.
- Due to the need to open and close the mold to remove the work piece, part geometry is limited.
- If the semi-permanent casting method is used, internal part geometry may be complex.
- Due to the nature of the mold, the metal casting will solidify rapidly. This will result in a smaller grain structure, producing a casting with superior mechanical properties.
- More uniform properties throughout the material of the cast part may also be observed with permanent mold casting.
- Closer dimensional accuracy as well as excellent surface finish of the part, is another advantage of permanent mold casting over most expendable metal casting processes.
- In industrial manufacture permanent mold casting results in a lower percentage of rejects than many expendable mold processes.

- There is a limitation on the size of cast parts manufactured by this process.
- The initial setup cost are high, making permanent mold casting unsuitable for small production runs.
- Permanent mold casting can be highly automated.
- This manufacturing process is useful in industry for high volume runs. When set up, it can be extremely economical with a high rate of production.

6.2. Slush casting

Slush casting is a variation of permanent mold casting that is used to produce hollow parts. In this method neither the strength of the part nor its internal geometry can be controlled accurately. This metal casting process is used primarily to manufacture toys and parts that are ornamental in nature, such as lamp bases and statues.

The process.

When producing a cast part using the slush casting method, a permanent mold is employed and set up. See basic permanent mold casting. The mold is clamped together and prepared for pouring.

Figure 66 - Mold for slush casting ready to be poured

After pouring the mold will set, as solidification begins to take place.

Figure 67 - Mold for slush casting immediately after pouring

The main principle of this casting process relies on the fact that when a metal casting hardens in a mold, it will solidify from the mold wall towards the inside of the casting. In other words a metal skin forms first, (as the external geometry of the part). This skin thickens as more of the metal casting's material converts to a solid state.

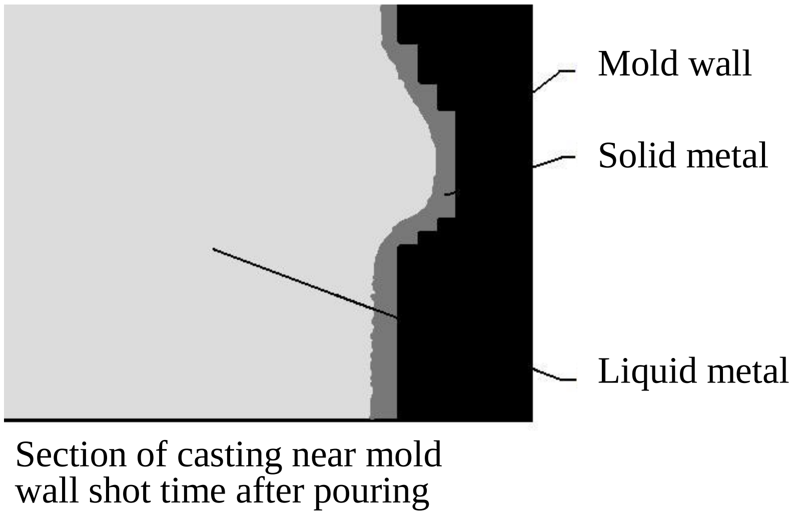


Figure 68 - Solidification can be used to start at interface between molten metal and mold surfaces

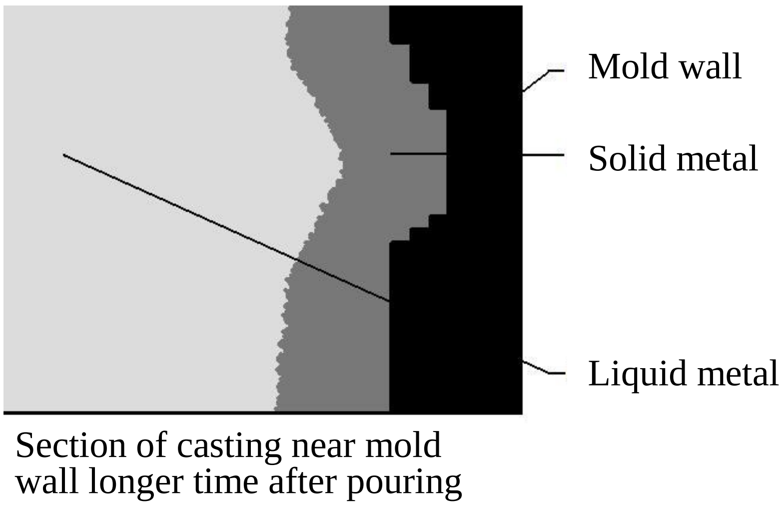


Figure 69 - Solidification process from mold-casting interface towards inner regions of the material thickness of this solid section increases with time

Figure 70 - Mold for slush casting gross sectional view of inside of casting a certain amount of time (T_1) after pouring

Figure 71 - Mold for slush casting gross sectional view of inside of casting a certain amount of time (T_2) after pouring also note ($T_2 > T_1$)

Figure 72 - Mold for slush casting gross sectional view of inside of casting a certain amount of time (T_3) after pouring also note ($T_3 > \boldsymbol{T_2}$)

In slush mold casting, during the solidification of the material, when the solid-liquid boundary has reached a certain point, the mold is turned over and the remaining liquid metal from the casting is poured out.

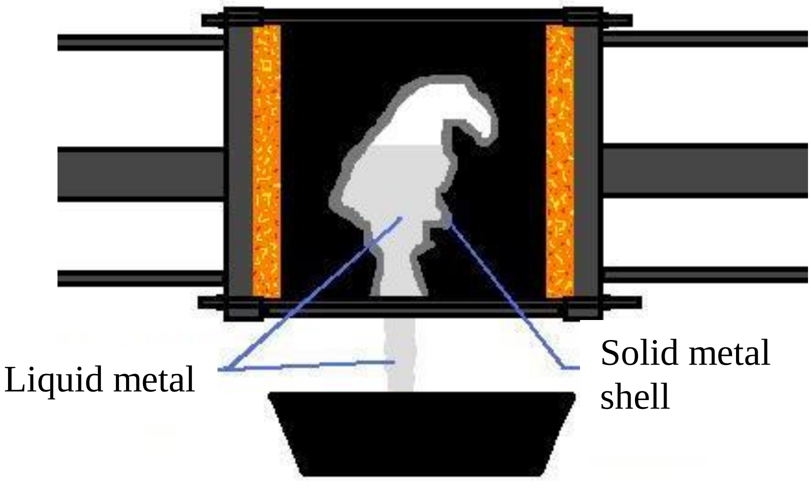


Figure 73 - The liquid metal from the interior of the casting is poured out before the entire mass of molten material can harden leaving only the solidified outer shell

This will leave only the solidified skin with the exterior geometry of the metal cast part and a hollow interior. The longer the metal casting was allowed to solidify before pouring out the excess metal, the greater the casting's wall thickness will be.

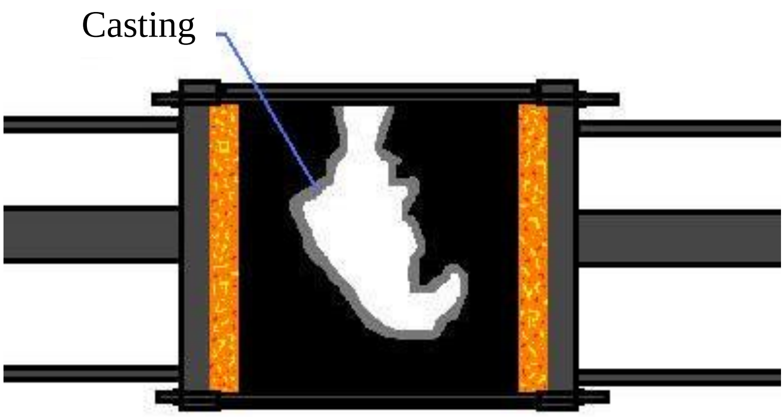


Figure 74 - Metal in solidified outer shell is all that remains in mold

The cast part is then removed from the die and allowed to cool.

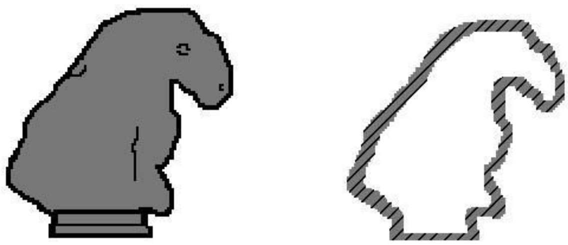


Figure 75 - Final product of slush casting process (shown with section view)

Properties and considerations of manufacturing by slush casting:

- Slush casting is a type of permanent mold casting, therefore many of the basic principles of a permanent mold process will apply.
- Slush casting is mainly suited to lower melting point materials, zinc, tin, or aluminum alloys are commonly slush cast in manufacturing industry.
- With this process you need to have a mechanical means of turning over the mold in order to pour out the molten metal from the cast part.

- When manufacturing by slush casting it is difficult to accurately control the metal casting's strength and other mechanical properties.
- The casting's internal geometry cannot be effectively controlled with this process.
- The hollow metal castings manufactured by this process are lighter than solid parts and save on material.
- Good surface finish and accurate exterior geometry are possible with the slush casting manufacturing process.

6.3. Pressure casting

Pressure casting, also known in manufacturing industry as low pressure casting or pressure pouring, is another variation of permanent mold casting. Instead of pouring the molten metal into the casting and allowing gravity to be the force that distributes the liquid material through the mold, pressure casting uses air pressure to force the metal through the gating system and the metal casting's cavity. This process can be used to cast high quality manufactured parts. Often steel castings are cast in graphite molds using this process. For example, in industry, steel railroad car wheels are cast with this method.

The process.

This is a permanent mold process and the manufacture of the mold in pressure casting is standard in most regards, see basic permanent mold casting. Two blocks are machined extremely accurately, so they can open and close precisely for removal of metal parts. The casting's gating system is machined into the mold. The gating system is set up so that the molten material flows into the mold from the bottom instead of the top, (like in gravity fed processes).

The mold is set up above the supply of liquid metal to be used for the casting. A refractory tube goes from the entrance of the gating system down into the molten material. During manufacture by this process, the chamber that the liquid material is in is kept air tight. When the mold is prepared and ready for the pouring of the metal casting, air pressure is applied to the chamber.

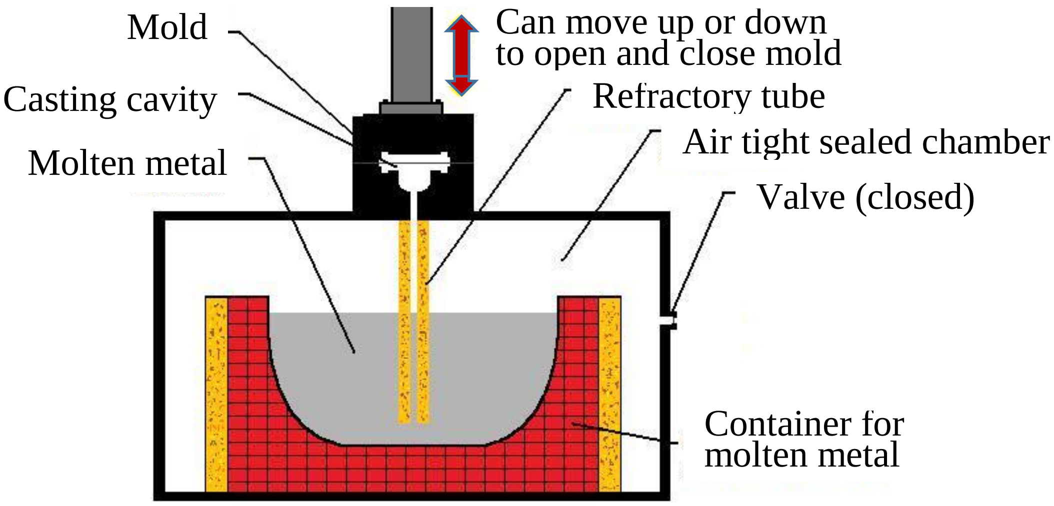


Figure 76 - Pressure casting mold is in place and operation is ready to begin

This creates pressure on the surface of the liquid, that in turn forces molten material up the refractory tube and throughout the mold.

Pressure used in pressure casting is usually low, 15 lbs/in^2 could be typical for industrial manufacture using this process.

The air pressure is maintained until the metal casting has hardened within the mold. Once the cast part has solidified, the mold is opened and the part is removed.

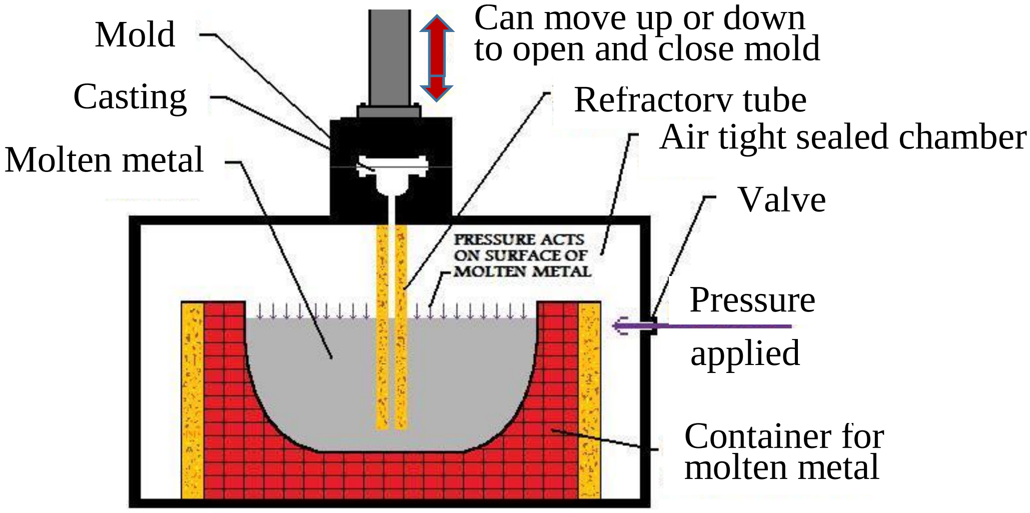


Figure 77 - Pressure is applied to the air-tight chamber from some source through the valve

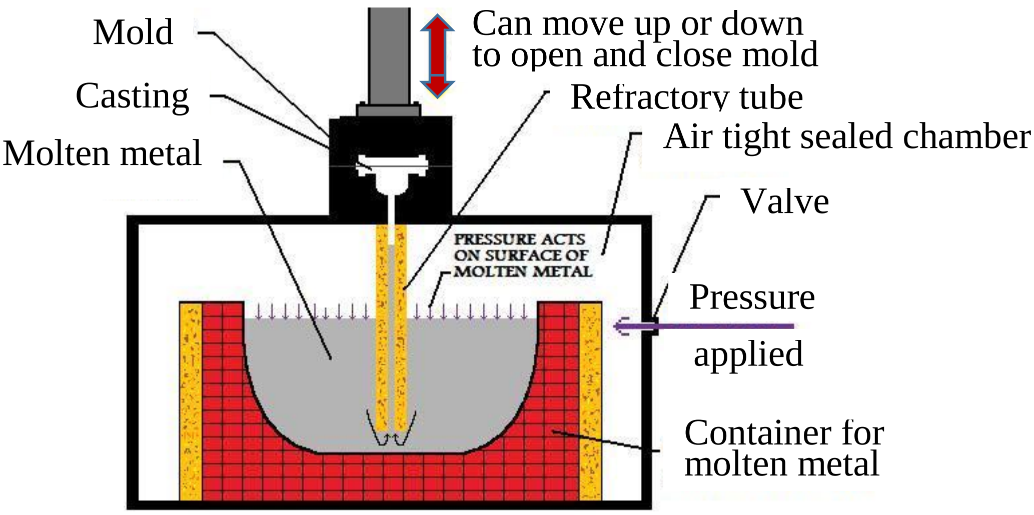


Figure 78 - Pressure difference between chamber and mold forces mental to flow up the refractory tube

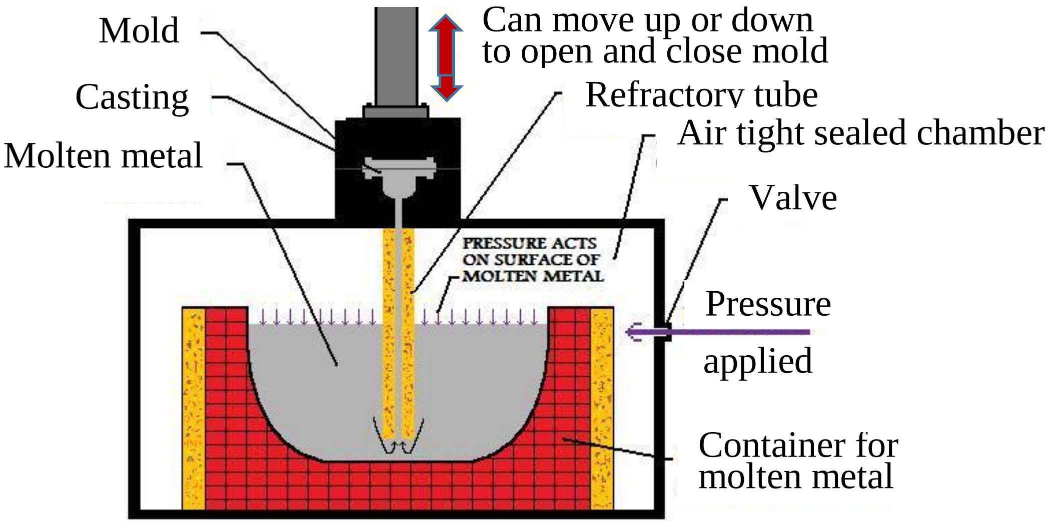


Figure 79 - The force of the pressure causes molten metal to fill the mold pressure is applied during the solidification of the casting

Properties and considerations of manufacturing by pressure casting:

- Pressure casting manufacture can be used to produce metal castings with superior mechanical properties, good surface finish, and close dimensional accuracy.
- Like in other permanent mold methods, the mold needs to be able to open and close for removal of the work piece. Therefore, very complicated casting geometry is limited.
- Since the refractory tube is submersed in the molten material, the metal drawn for the casting comes from well below the surface. This metal has had less exposure to the environment than the material at the top. Gas trapped in the metal as well as oxidation effects are greatly reduced.
- The high setup cost makes pressure casting not efficient for small runs, but an excellent productivity rate makes it suitable for large batch manufacture.

6.4. Vacuum permanent mold casting

Vacuum permanent mold casting is a permanent mold casting process employed in manufacturing industry that uses the force caused by an applied vacuum pressure to draw molten metal into and through the mold's gating system and casting cavity. This process has a similar name to vacuum mold casting discussed in the expendable mold process section; however these are two completely different manufacturing processes and should not be confused with each other.

The process.

A permanent mold containing the part geometry and the gating system is created, (usually accurately machined), similar to the molds employed in the other permanent mold processes. The mold in vacuum mold casting is much like the mold in the pressure casting manufacturing process, in that the gating system is designed so that the flow of molten material starts at the bottom and flows upwards.

Figure 80 - Permanent mold for vacuum casting

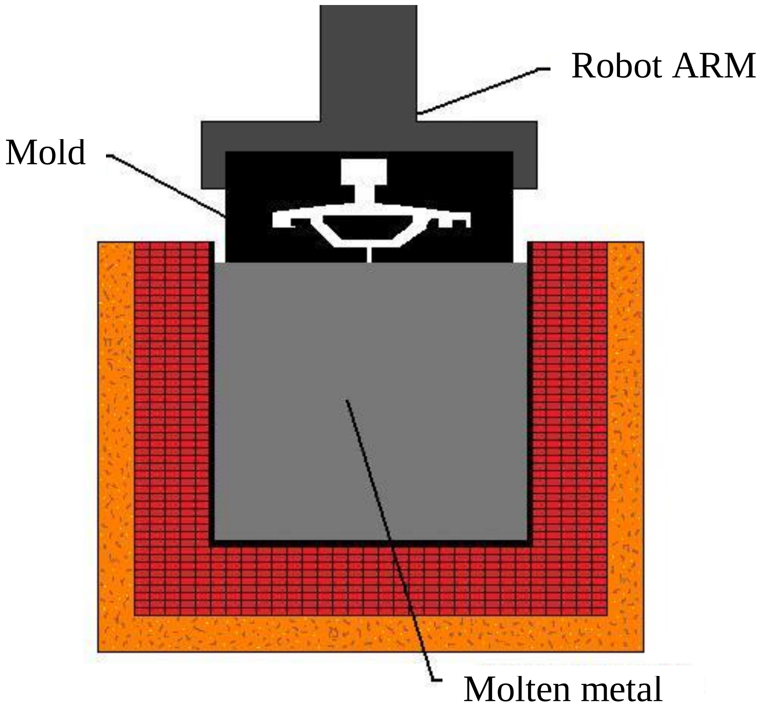


Figure 81 - The first stage

The mold is suspended over a supply of liquid metal for the casting by some mechanical device, possibly a robot ARM.

A vacuum force is applied to the top of the mold. The reduced pressure within the mold causes molten metal to be drawn up through the gating system and casting cavity.

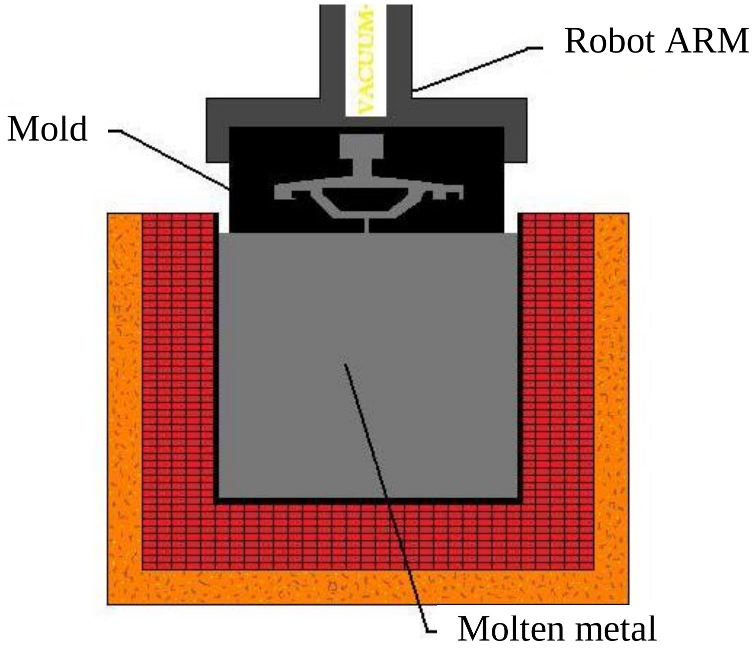


Figure 82 - The second stage

As the casting solidifies, the mold is withdrawn from its position over the molten metal and opened to release the casting.

Properties and considerations of manufacturing by vacuum casting:

- This manufacturing process can produce metal castings with close dimensional accuracy, good surface finish, and superior mechanical properties.
- Castings with thin walled sections may be manufactured using this technique.
- This process is very much like pressure casting in the way the mold is filled, but since vacuum force is used instead of air pressure, gas related defects are reduced.
- Set up cost make this manufacturing process more suitable to high volume production, instead of small batch manufacture.

6.5. Die casting

Die casting is a permanent mold manufacturing process that was developed in the early 1900's. Die casting manufacture is characteristic in that it uses large amounts of pressure to force molten metal through the mold. Since so much pressure is used to ensure the flow of metal through the mold, metal castings with great surface detail, dimensional accuracy, and extremely thin walls can be produced. Wall thickness within castings can be manufactured as small as .02in (.5mm). The size of industrial metal castings created using this process vary from extremely small to around 50lbs. Typical parts made in industry by die casting include tools, toys, carburetors, machine components, various housings, and motors.

The process.

The mold.

Like in all permanent mold manufacturing processes, the first step in die casting is the production of the mold. The mold must be accurately created as two halves that can be opened and closed for removal of the metal casting, similar to the basic permanent mold casting_process. The mold for die casting is commonly machined from steel and contains all the components of the gating system. Multi-cavity die are employed in manufacturing industry to produce several castings with each cycle. Unit dies which are a combination of smaller dies are also used to manufacture metal castings in industry.

In a die casting production setup, the mold, (or die), is designed so that its mass is far greater than that of the casting. Typically the mold will have 1000 times the mass of the metal casting.

So, a 2 pound part will require a mold weighing a ton! Due to the extreme pressures and the continuous exposure to thermal gradients from the molten metal, wearing of the die can be a problem. However in a well maintained manufacturing process, a die can last hundreds of thousands of cycles before needing to be replaced.

Die casting machines.

In addition to the opening and closing of the mold to prepare for and remove castings, it is very important that there is enough force that can be applied to hold the two halves of the mold together during the injection of the molten metal. Flow of molten metal under such pressures will create a tremendous force acting to separate the die halves during the process. Die casting machines are large and strong, designed to hold the mold together against such forces.

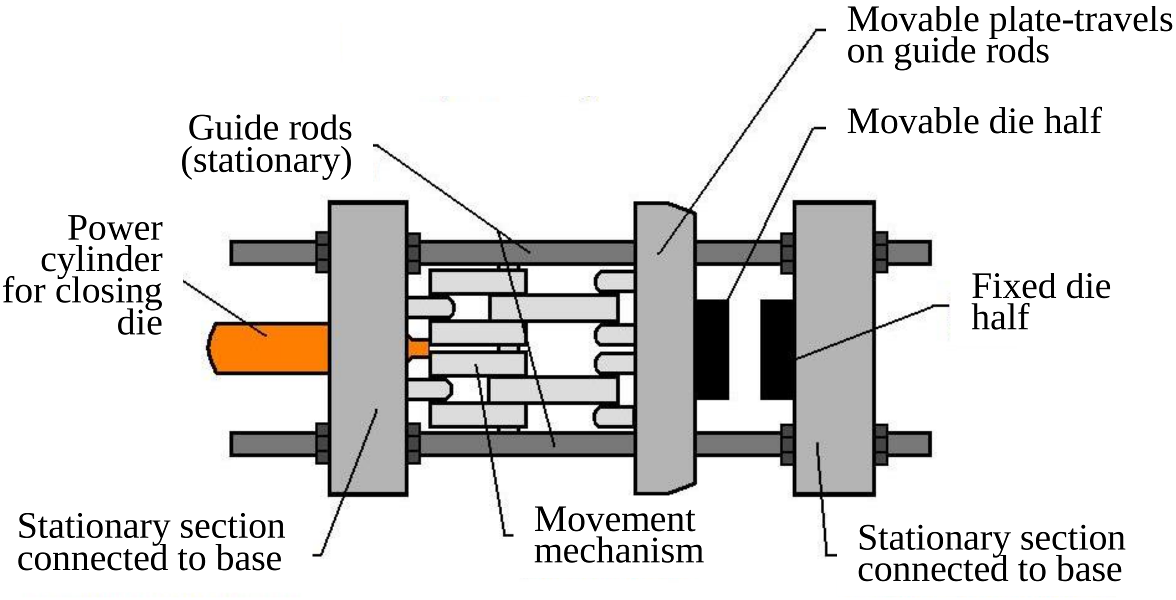


Figure 83 - Cold chamber die casting machine (top view)

In manufacturing industry, die casting machines are rated on the force with which they can hold the mold closed. Clamping forces for these machines vary from around 25 to 3000 tons.

Injection of molten metal.

In industrial manufacture the process of die casting falls into two basic categories, hot chamber die casting and cold chamber die casting. Each process will be discussed specifically in more detail later. Although these processes vary from each other, both employ a piston or plunger to force molten metal to travel in the desired direction.

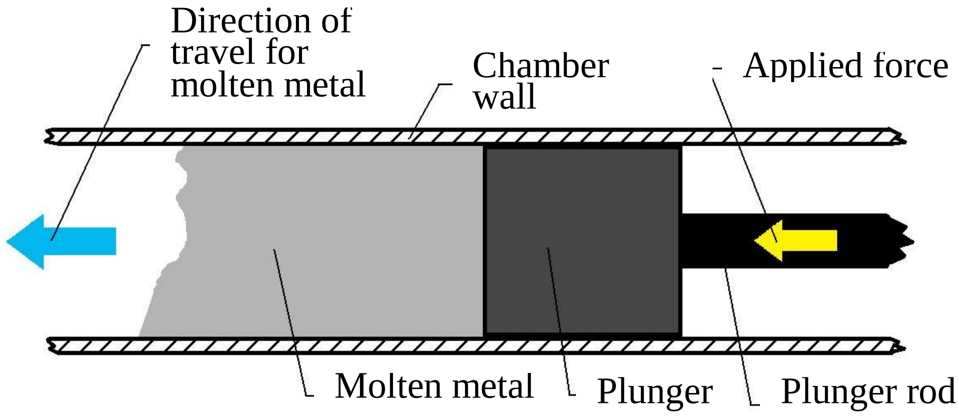


Figure 84 - Basic principle of die casting

The pressure at which the metal is forced to flow into the mold in die casting manufacture is on the order of 1000psi to 50000psi (7MPa to 350MPa). This pressure is accountable for the tremendously intricate surface detail and thin walls that are often observed in metal castings manufactured by this technique.

Once the mold has been filled with molten metal, the pressure is maintained until the casting has hardened. The mold is then opened and the casting is removed. Ejector pins built into the mold assist in the removal of the metal casting. In most manufacturing operations, the internal surfaces of the mold are sprayed with a lubricant before every cycle. The lubricant will assist in cooling down the dies as well as preventing the metal casting from sticking to the mold.

After the casting has been removed and the lubricant applied to the mold surfaces, the die are clamped together again then the cycle will repeat itself. Cycle times will differ depending upon the details of each specific die casting manufacturing technique.

In some instances, very high rates of production have been achieved using this metal casting process.

Insert molding.

With the die casting process, shafts, bolts, bushings and other parts can be inserted into the mold and the metal casting may be formed around these parts. This is called insert molding, once solidified these parts become one with the casting.

To help with the integration of the part into the casting, the part may be grooved or knurled providing a stronger contact surface between the part and the molten metal.

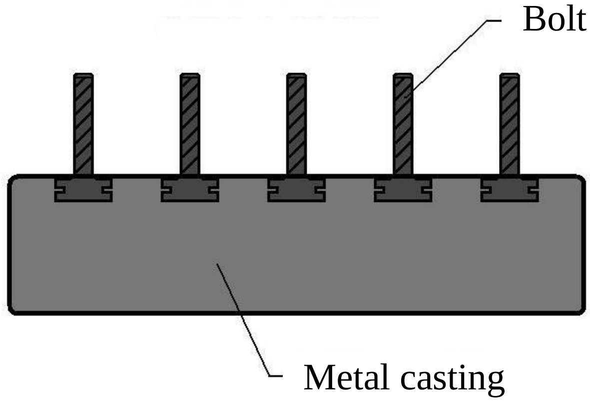


Figure 85 - Grooved bolts cast into a part

Properties and considerations of manufacturing by die casting:

- Metal castings with close tolerances, tremendous surface detail, and thin intricate walls can be manufactured using this process.
- Due to the rapid cooling at the die walls smaller grain structures are formed, resulting in manufactured metal castings with superior mechanical properties. This is especially true of the thinner sections of the casting.
- When manufacturing by this process, it is of concern to keep the mold cool. Die may have special passages built into them that water is cycled through in order to keep down thermal extremes.
- Due to the high pressures, a thin flash of metal is usually squeezed out at the parting line. This flash has to be trimmed latter from the casting.
- Since the mold is not permeable, adequate vents need to be provided for the elimination of gases during the metal casting process. These vents are usually placed along the parting line between the die.
- High production rates are possible in die casting manufacture.
- Ejector pins will usually leave small round marks on the metal casting. These can be observed on the surfaces of manufactured parts.
- The need to open and close the mold limits some of the shapes and geometries that may be cast using this manufacturing process.
- Equipment cost for die casting are generally high.
- Die casting manufacture can be highly automated, making labor cost low.
- Die casting is similar to most other permanent mold casting processes in that high set up cost, and high productivity make it suitable for larger batch manufacture and not small production runs.

6.6. Hot chamber die casting

Hot chamber die casting is one of the two main techniques in the manufacturing process of die casting. This section will primarily discuss the specific details of the hot chamber process and contrast the differences between hot chamber die casting and cold chamber die casting, which is the other branch of die casting manufacture.

Hot chamber process.

A similar characteristic of either die casting process is the use of high pressure to force molten metal through a mold called a die. Many of the superior qualities of castings manufactured by die casting, (such as great surface detail), can be attributed to the use of pressure to ensure the flow of metal through the die. In hot chamber die casting manufacture, the supply of molten metal is attached to the die casting machine and is an integral part of the casting apparatus for this manufacturing operation.

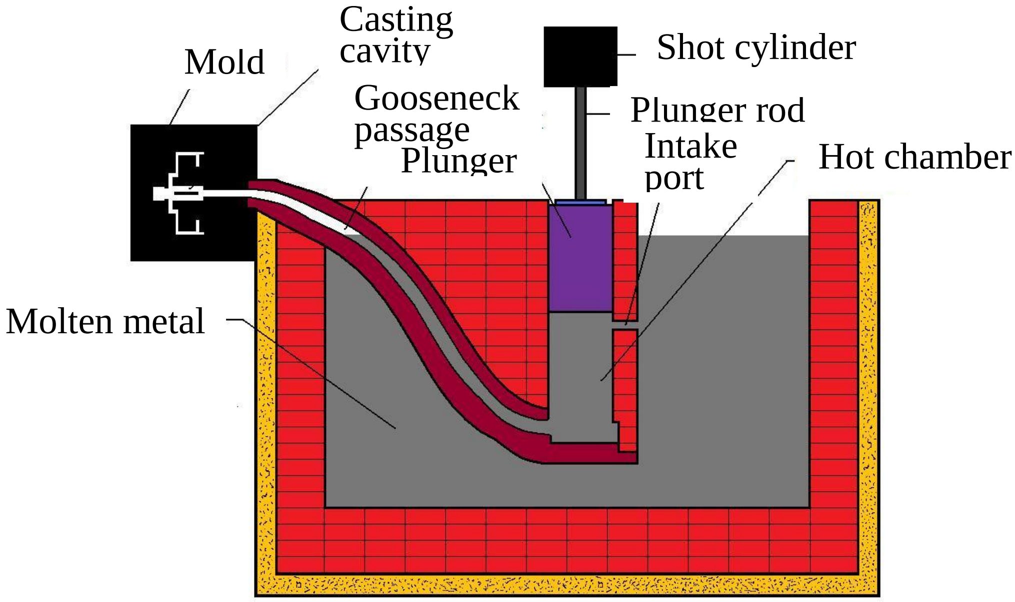


Figure 86 - Hot chamber die casting

The shot cylinder provides the power for the injection stroke. It is located above the supply of molten metal. The plunger rod goes from the shot cylinder down to the plunger, which is in contact with the molten material. At the start of a casting cycle, the plunger is at the top of a chamber (the hot-chamber). Intake ports allow this chamber to fill with liquid metal. As the cycle begins, the power cylinder forces the plunger downward. The plunger travels past the ports, cutting off the flow of liquid metal to the hot chamber. Now there should be the correct amount of molten material in the chamber for the "shot" that will be used to fill the mold and produce the casting.

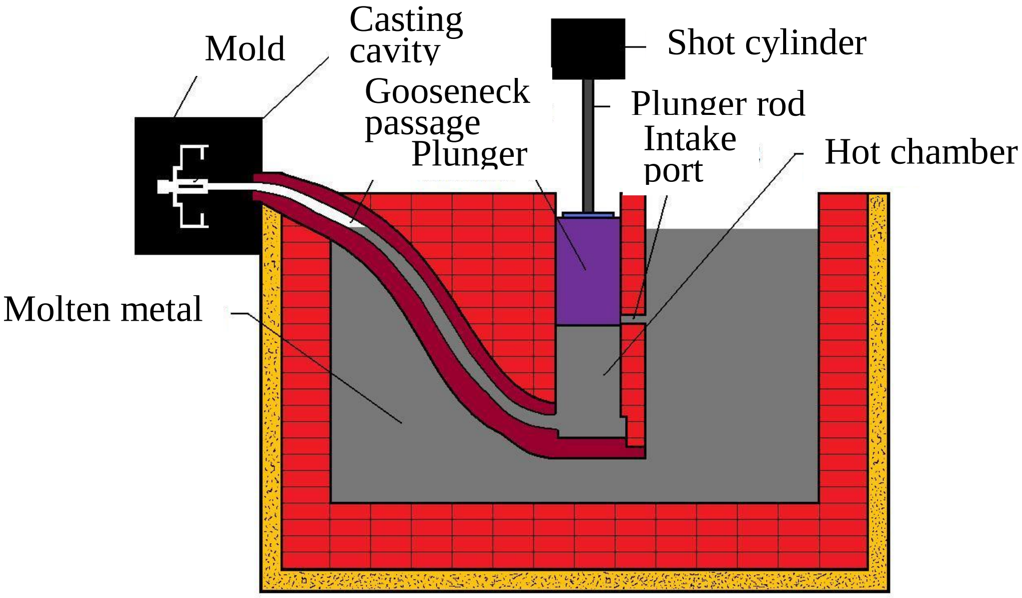


Figure 87 - Hot chamber die casting

At this point the plunger travels further downward, forcing the molten metal into the die. The pressure exerted on the liquid metal to fill the die in hot chamber die casting manufacture usually varies from about 700psi to 5000psi (5MPa to 35 MPa). The pressure is held long enough for the casting to solidify.

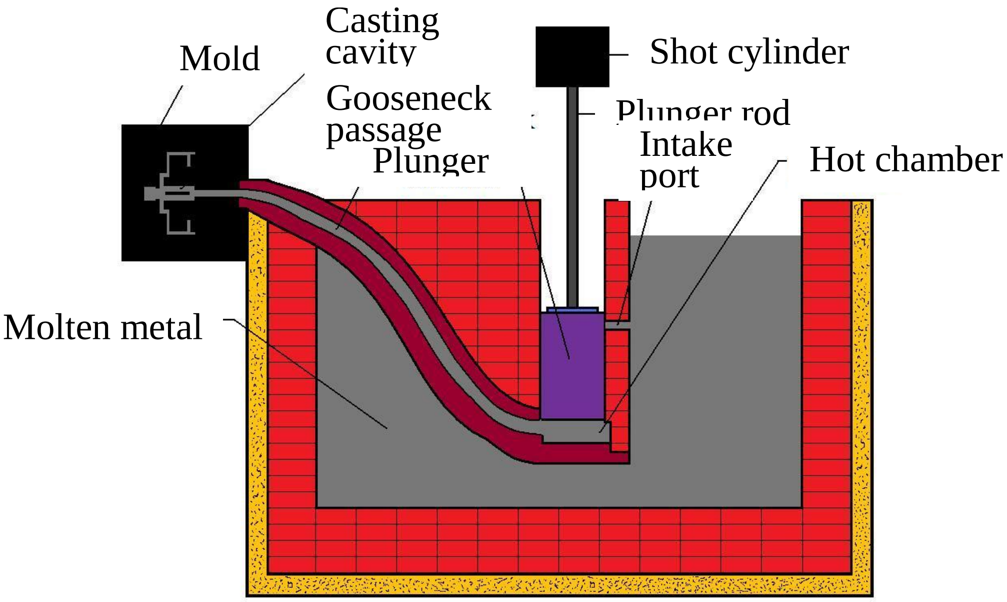


Figure 88 - Hot chamber die casting

In preparation for the next cycle of casting manufacture, the plunger travels back upward in the hot chamber exposing the intake ports again and allowing the chamber to refill with molten material.

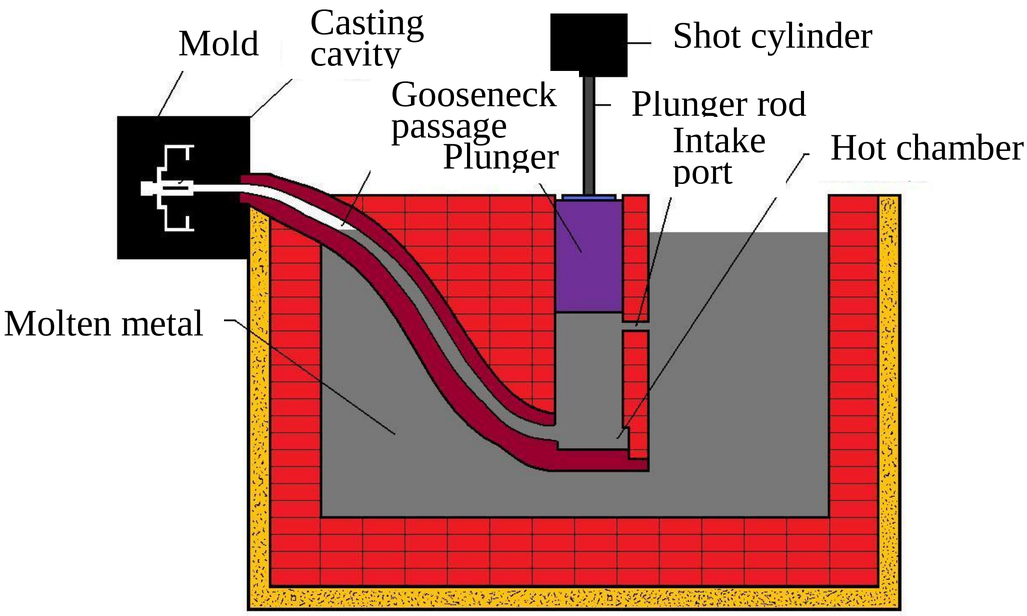


Figure 89 - Hot chamber die casting

For more extensive details on the setup of the mold, the die casting process, or the properties and considerations of manufacturing by die casting see die casting for the basics of the process.

Hot chamber die casting has the advantage of a very high rate of productivity. During industrial manufacture by this process one of the disadvantages is that the setup requires that critical parts of the mechanical apparatus, (such as the plunger), must be continuously submersed in molten material.

Continuous submersion in a high enough temperature material will cause thermal related damage to these components rendering them inoperative. For this reason, usually only lower melting point alloys of lead, tin, and zinc are used to manufacture metal castings with the hot chamber die casting process.

6.7. Cold chamber die casting

Cold chamber die casting is the second of the two major branches of the die casting manufacturing process. This section will discuss cold chamber die casting specifically and contrast it with the hot chamber process discussed previously. For a basic view of die casting in general see die casting manufacture.

Cold chamber process.

Cold chamber die casting is a permanent mold metal casting process. A reusable mold, gating system and all, is employed. It is most likely machined precisely from two steel blocks. Large robust machines are used to exert the great clamping force necessary to hold the two halves of the mold together against the tremendous pressures exerted during the manufacturing process.

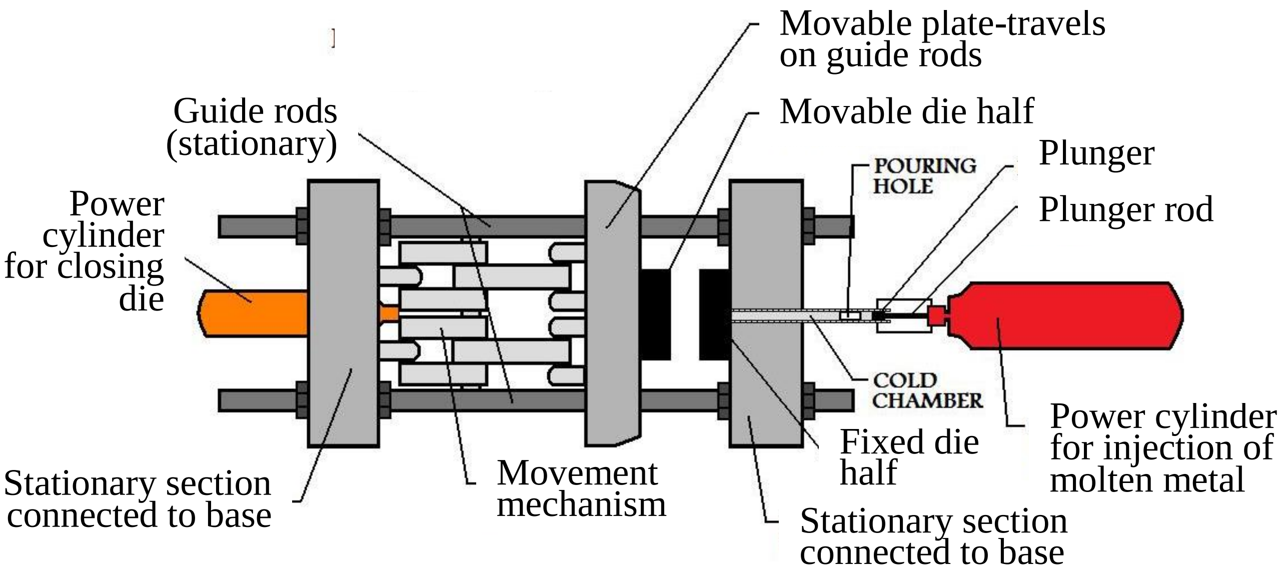


Figure 90 - old chamber die casting machine
(top veiw)

A metal shot chamber, (cold-chamber), is located at the entrance of the mold. A piston is connected to this chamber, which in turn is connected to a power cylinder.

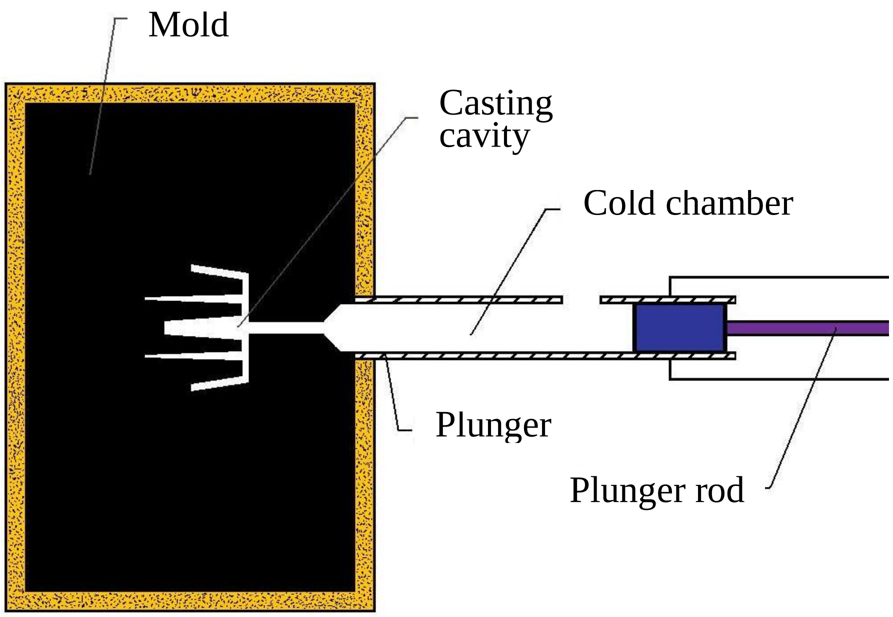


Figure 91 - Cold chamber die casting

At the start of the manufacturing cycle, the correct amount of molten material for a single shot is poured into the shot chamber from an external source holding the material for the metal casting.

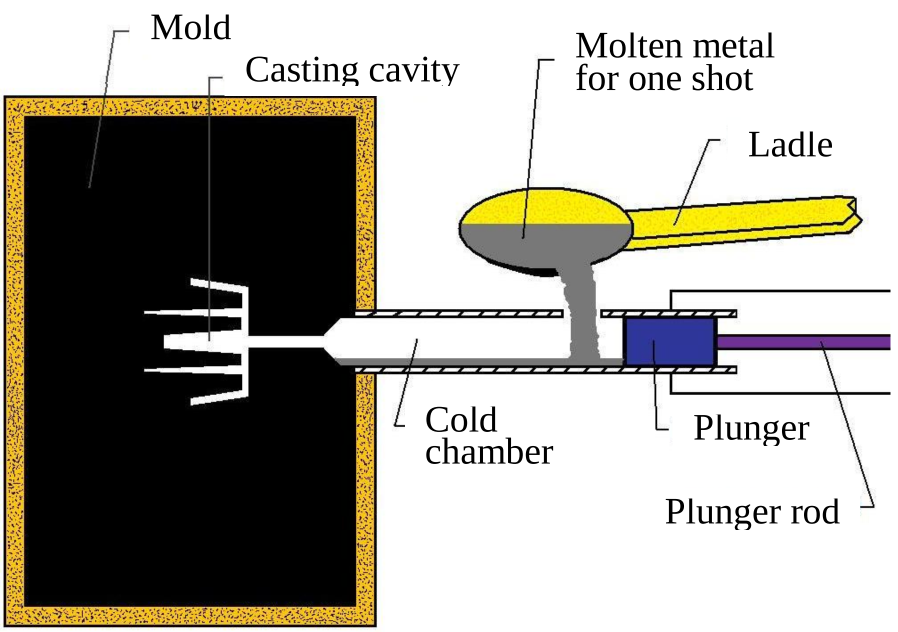


Figure 92 - Cold chamber die casting

The power cylinder forces the piston forward in the chamber, cutting off the intake port. The power cylinder moving the piston forward forces the molten material into the casting mold with great pressure.

Pressure causes the liquid metal to fill in even thin sections of the metal casting and press the mold walls for great surface detail. The pressure is maintained some time after the injection phase of die casting manufacture.

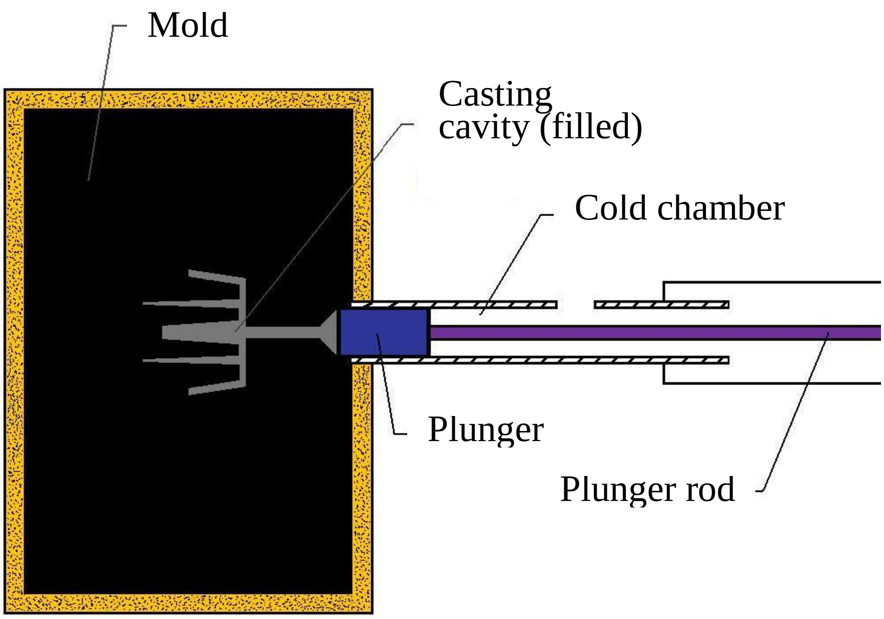


Figure 93 - Cold chamber die casting

Once the metal casting begins to solidify, the pressure is released. Then the mold is opened and the casting is removed by way of ejector pins. The mold is sprayed with lubricant before closing again, and the piston is withdrawn in the shot chamber for the next cycle of production.

Cold chamber die casting for manufacture.

The main difference between cold-chamber die casting and hot-chamber die casting manufacture is that in the cold-chamber process the molten metal for the casting is introduced to the shot chamber from an external source, while in the hot chamber process the source of molten material is attached to the machine. In the hot-chamber process, certain machine apparatus is always in contact with molten metal. For this reason, higher melting point materials will create a problem for the machinery in a hot-chamber metal casting setup. Since the liquid metal is brought in from an outside source, the die casting machinery is able to stay much cooler in a cold-chamber process.

Consequently, higher melting point alloys of aluminum, brass, copper, and aluminum-zinc are often metal cast in manufacturing industry using cold chamber die casting. It is very possible to manufacture castings from lower melting point alloys using the cold-chamber method.

When considering industrial metal casting manufacture, however, the advantages of production by the hot-chamber process usually make it the more suitable choice for lower melting point alloys.

In the cold chamber die casting process, material must be brought in for every shot or cycle of production. This slows down the production rate for metal casting manufacture. Where in the hot chamber process, castings can be constantly output. Cold chamber die casting should still be considered a high production manufacturing process.

In comparison with the hot die casting process, the cold die casting process requires the application of more pressure. The pressure at which the molten metal is forced into and fills the die cavity in cold chamber metal casting manufacture typically outranks the pressure used to fill the die in hot chamber metal casting by about an order of magnitude. Pressures of 3000psi to 50000psi (20MPa to 350MPa) may be used in manufacturing industry to fill the mold cavities with molten material during cold chamber die casting manufacture.

Castings manufactured by cold chamber die casting have all the advantages characteristic of the die casting process, such as intricate detail, thin walls, and superior mechanical properties. The significant initial investment into this manufacturing process makes it suitable for high production applications.

6.8. True centrifugal casting

The manufacturing process of centrifugal casting is a metal casting technique, that uses the forces generated by centripetal acceleration to distribute the molten material in the mold. Centrifugal casting has many applications in manufacturing industry today. The process has several very specific advantages. Cast parts manufactured in industry include various pipes and tubes, such as sewage pipes, gas pipes, and water supply lines, also bushings, rings, the liner for engine cylinders, brake drums, and street lamp posts. The molds used in true centrifugal casting manufacture are round, and are typically made of iron, steel, or graphite. Some sort of refractory lining or sand may be used for the inner surface of the mold.

The process.

It is necessary when manufacturing a cast part by the true centrifugal metal casting process, using some mechanical means, to rotate the mold. When this process is used for industrial manufacture, this is accomplished by the use of rollers. The mold is rotated about its axis at a predetermined speed. Molds for smaller parts may be rotated about a vertical axis. However, most times in true centrifugal casting manufacture the mold will be rotated about a horizontal axis. The effects of gravity on the material during the metal casting process make it particularly necessary to cast longer parts with forces generated from horizontal rather than vertical rotation.

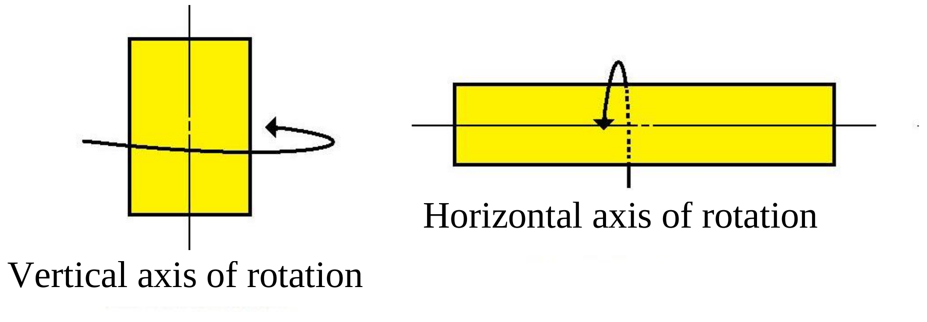


Figure 94 - Vertical vs horizontal rotation

The molten material for the cast part is introduced to the mold from an external source, usually by means of some spout. The liquid metal flows down into the mold. Once inside the cavity, the centripetal forces from the spinning mold force the molten material to the outer wall. Molten material for the casting may be poured into a spinning mold or the rotation of the mold may begin after pouring has occurred.

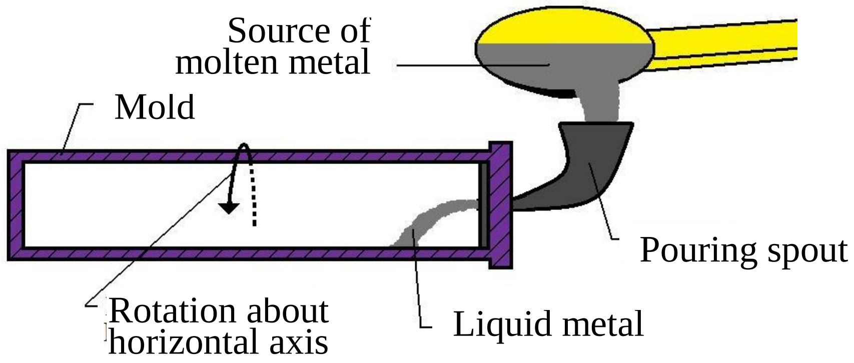


Figure 95 - Pouring in true centrifugal casting

The metal casting will harden as the mold continues to rotate.

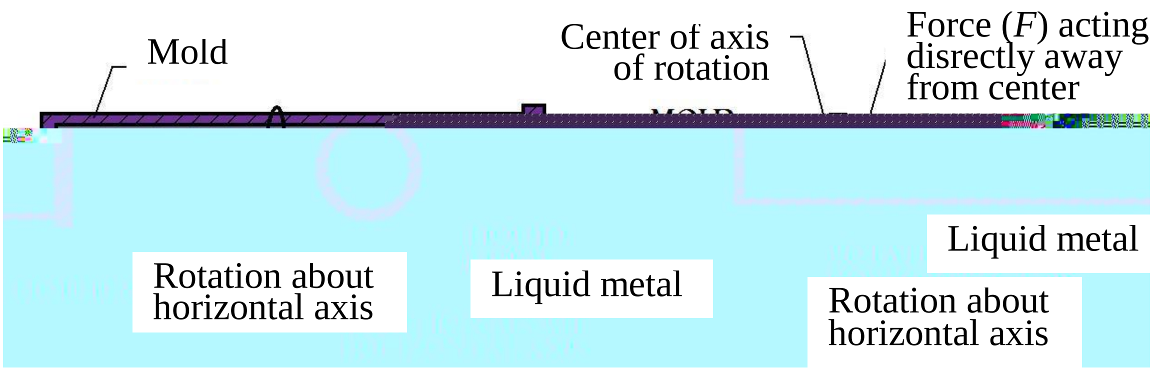


Figure 96 - Solidification in true centrifugal casting

It can be seen that this casting process is very well suited for the manufacture of hollow cylindrical tubes. The forces used in this technique guarantee good adhesion of the casting material to the surface of the mold. Thickness of the cast part can be determined by the amount of material poured. The outer surface does not need to be round. Polygonal geometries such as squares and other shapes can be cast. However, due to the nature of the process, the inner surface of a part manufactured by true centrifugal casting must always be round.

During the pouring and solidification phase of true centrifugal casting, the forces at work play a large roll in the properties of castings manufactured by this process. It can be seen that forces will be greater in the regions further away from the center of the axis of rotation. The greater forces towards the rim will cause the regions of the metal casting nearer the outer surface to have a higher density than the sections located nearer the inner surface.

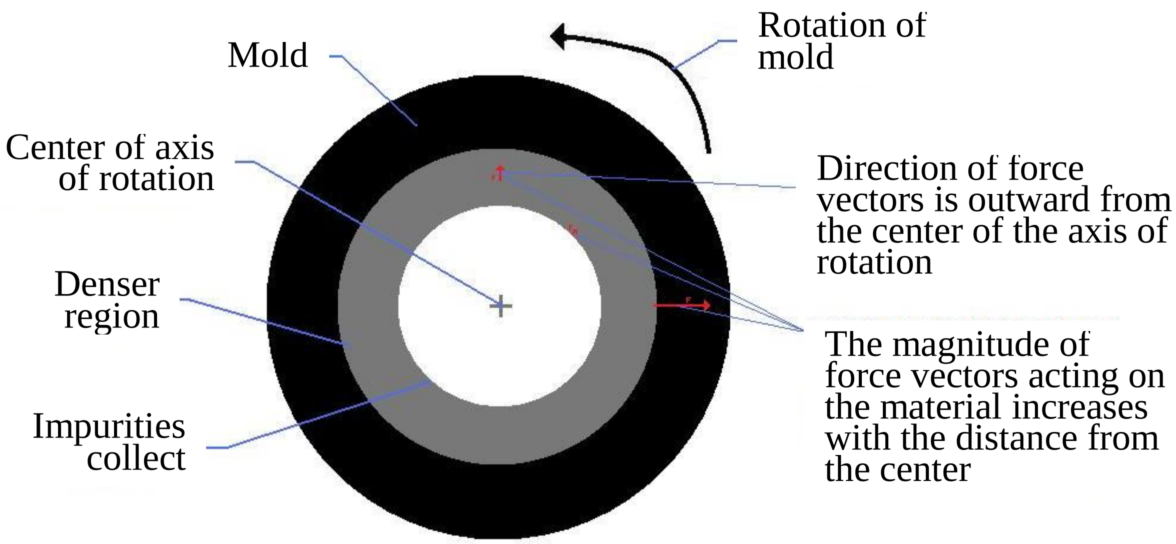


Figure 97 - Force vector diagram for true centrifugal casting (cross-section)

Most impurities within the material have a lower density than the metal itself, this causes them to collect in the inner regions of the metal casting, closer to the center of the axis of rotation. These impurities can be removed during the casting operation or they can be machined off later.

Properties and considerations of manufacturing by true centrifugal casting:

- True centrifugal casting is a great manufacturing process for producing hollow cylindrical parts.
- The metal casting's wall thickness is controlled by the amount of material added during the pouring phase.
- Rotational rate of the mold during the manufacture of the casting must be calculated carefully based on the mold dimensions and the metal being cast.
- If the rotational rate of the mold is too slow, the molten material for the casting will not stay adhered to the surface of the cavity. From the top half of the rotation it will rain metal within the casting cavity as the mold spins.
- This manufacturing operation produces metal cast parts without the need for sprues, risers, or other gating system elements, making this a very efficient industrial metal casting process, in terms of material usage.

- Since large forces press the molten material for the cast part against the mold wall during the manufacturing operation, good surface finish and detail are characteristic of true centrifugal casting.
- Quality castings with good dimensional accuracy can be produced with this process.
- Material of high density and with few impurities is produced in the outer regions of cylindrical parts manufactured by true centrifugal casting.
- Impurities, such as metal inclusions and trapped air, collect in the lower density inner regions of cylindrical parts cast by this process.
- These inner regions can be machined out of the cast part leaving only the dense, more pure material.
- Shrinkage is not a problem when manufacturing by true centrifugal casting, since material from the inner sections will constantly be forced to instantly fill any vacancies that may occur in outer sections during solidification.
- This method can produce very large metal castings. Cylindrical pipes 10 feet in diameter and 50 feet long have been manufactured using this technique.
- With the employment of a sand lining in the mold, it is possible to manufacture castings from high melting point materials such as iron and steels.
- This is a large batch production operation.
- True centrifugal casting is a manufacturing process that is capable of very high rates of productivity.

6.9. Semicentrifugal casting

Semicentrifugal casting manufacture is a variation of true centrifugal casting. The main difference is that in semicentrifugal casting the mold is filled completely with molten metal, which is supplied to the casting through a central sprue.

Castings manufactured by this process will possess rotational symmetry. Much of the details of the manufacturing process of semicentrifugal casting are the same as those of true centrifugal casting. For a better understanding of this process and centrifugal casting manufacture in general seetrue centrifugal casting. Parts manufactured in industry using this metal casting process include such things as pulleys, and wheels for tracked vehicles.

The process.

In semi-centrifugal casting manufacture a permanent mold may be employed. However, often industrial manufacturing processes will utilize an expendable sand mold. This enables the casting of parts from high temperature materials.

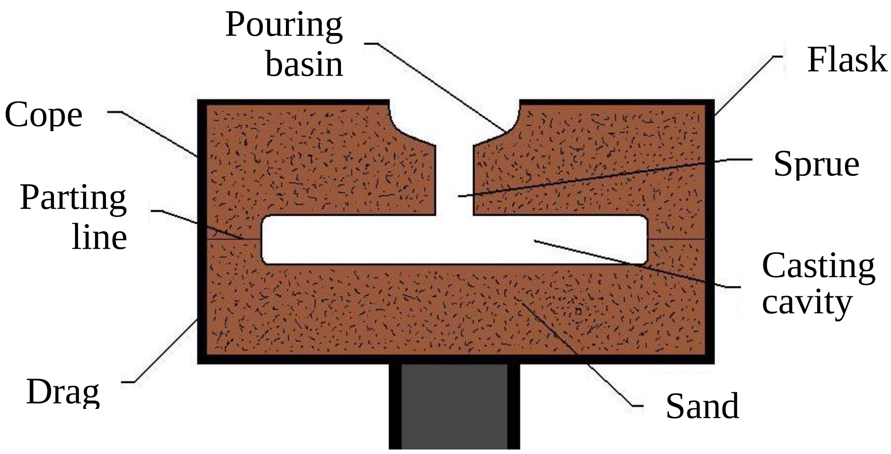


Figure 98 - Semicentrifugal casting expendable sand mold used to manufacture a wheel

The molten material for the metal casting is poured into a pouring basin and is distributed through a central sprue to the areas of the mold. The forces generated by the rotation of the mold ensure the distribution of molten material to all regions of the casting.

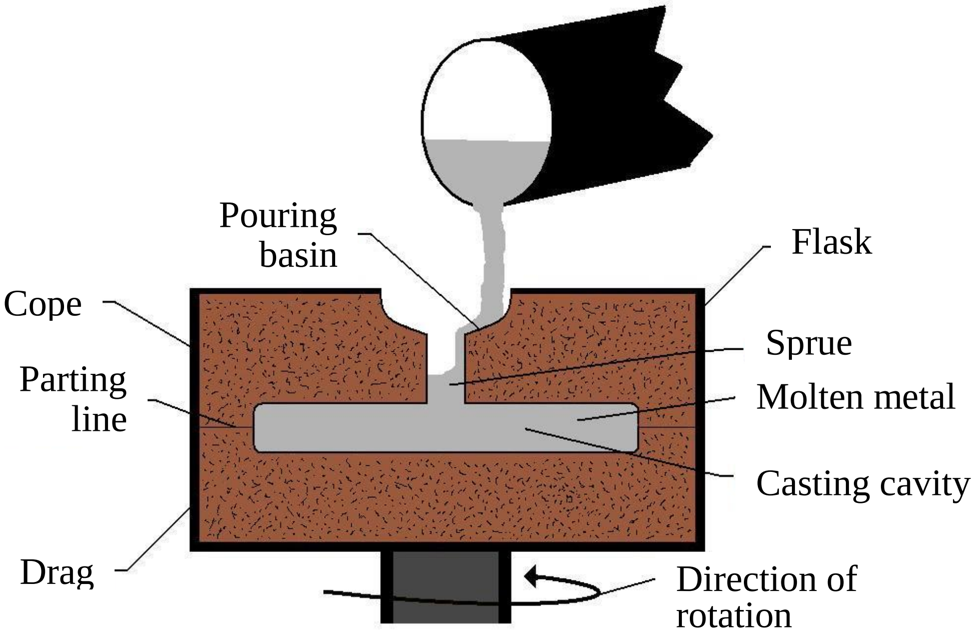


Figure 99 - Semicentrifugal casting pouring a wheel

As the metal casting solidifies in a rotating mold, the centripetal forces constantly push material out from the central sprue/riser. This material acts to fill vacancies as they form, thus avoiding shrinkage areas.

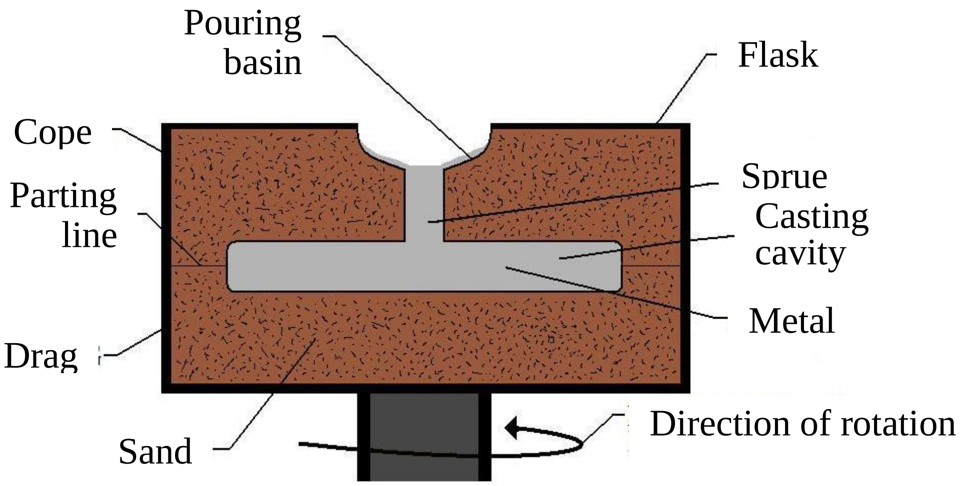


Figure 100 - Semicentrifugal casting solidification a wheel

The centripetal forces acting on the casting's material during the manufacturing process of semi centrifugal casting, play a large part in determining the properties of the final cast part. This is also very much the case with cast parts manufactured using the true centrifugal casting process. Forces acting in the true centrifugal process are similar to those that influence the material of a metal casting being manufactured by semi centrifugal casting.

When manufacturing by semi-centrifugal casting, the centripetal acceleration generated on the mass of molten metal by a rotating mold is the force that acts to fill the casting with this molten metal. This is also the force that continues to act on the material as the casting solidifies. The main thing to remember about centripetal forces is that the force will push in a direction that is directly away from the center of the axis of rotation.

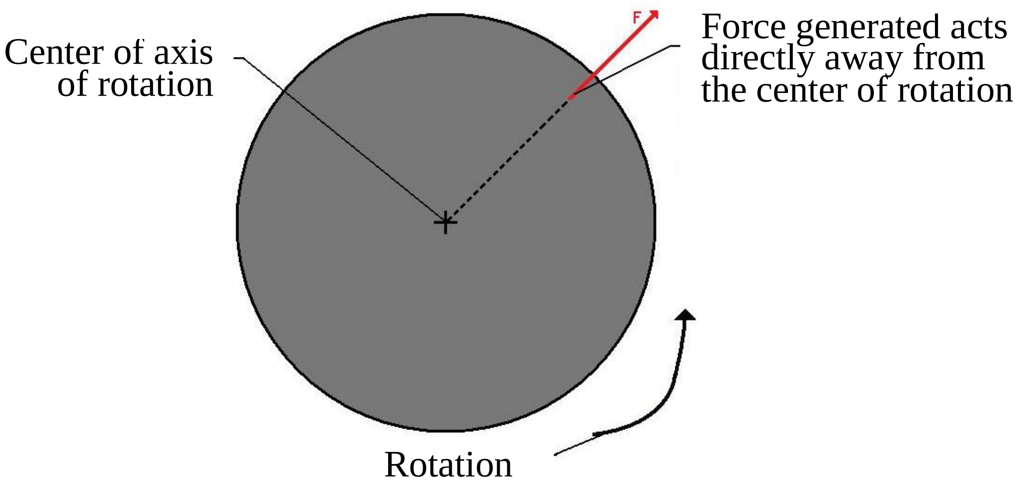


Figure 101 - Spinning wheel

Also, the farther away from the center of the axis of rotation, the greater the force.

It can be seen that during the semicentrifugal manufacturing process, the material in the outer regions of the casting, (further from the center of the axis of rotation), is subject to greater forces than the material in the inner regions.

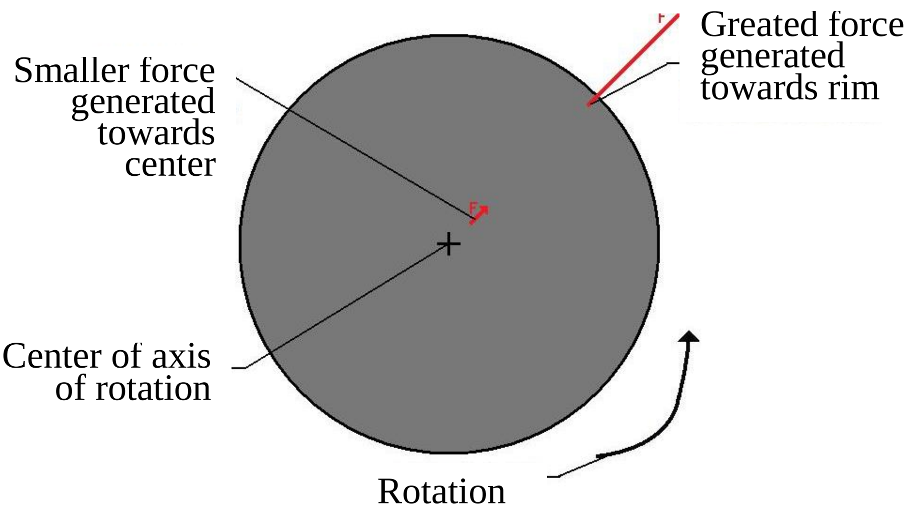


Figure 102 - Spinning wheel

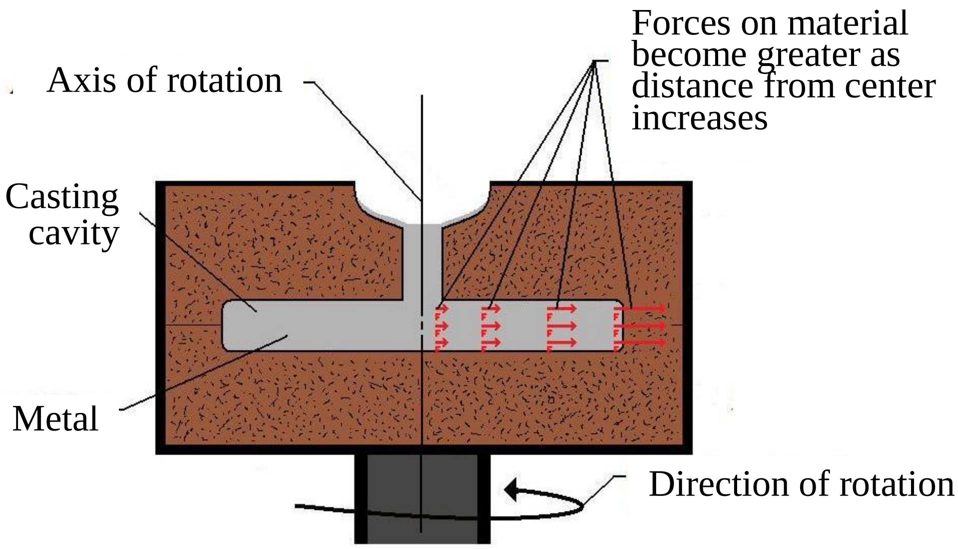


Figure 103 - Semicentrifugal casting

When the metal casting solidifies, the outer region of the cast part forms of dense material. The greater the forces under which the molten metal solidified, the denser the material in that region. So the density of a cast part manufactured by semicentrifugal casting will increase as you travel radially outward from the center.

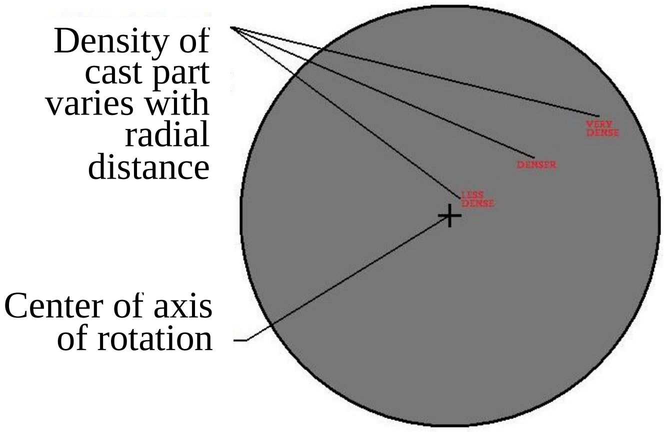


Figure 104 - Cast wheel

The high forces in the outer section that push the molten material against the mold wall also ensure a great surface finish of cast parts manufactured by semicentrifugal casting.

Another feature of this process, attributed to the usage of centripetal forces, is that impurities within the metal, (such as solid inclusions and trapped air), will form towards the inner regions of the casting.

This occurs because the metal itself is denser than the impurities, denser material subject to centripetal forces will tend to move towards the rim, forcing less dense material to the inner regions.

This particular detail is also a feature in other types of centrifugal casting manufacture.

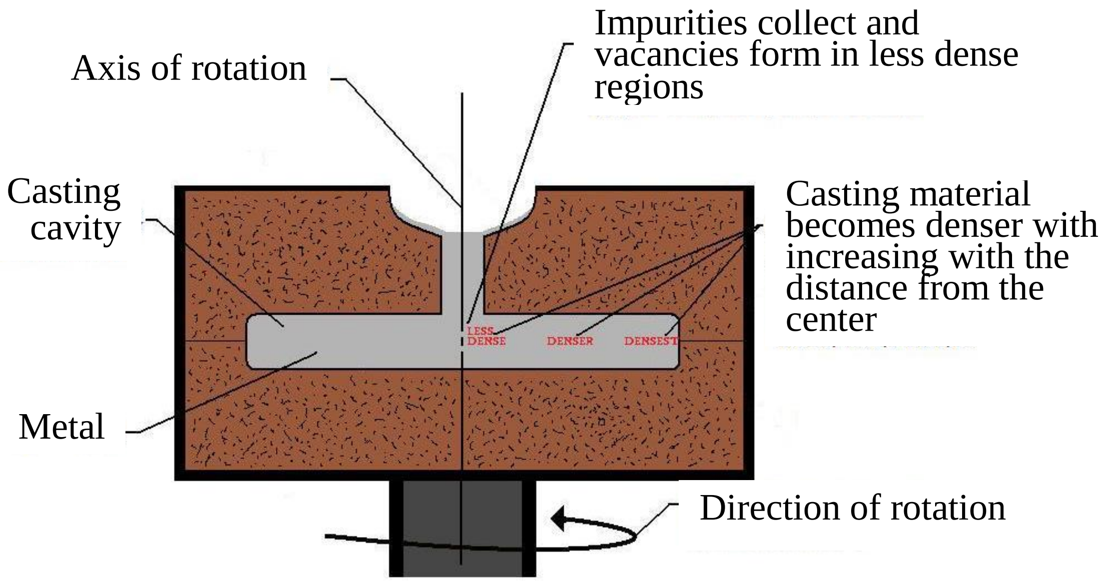


Figure 105 - Semicentrifugal casting

In industrial manufacture of parts by semicentrifugal casting, it is common to machine out the impurity filled center section, leaving only the purer, denser outer region as the final cast part.

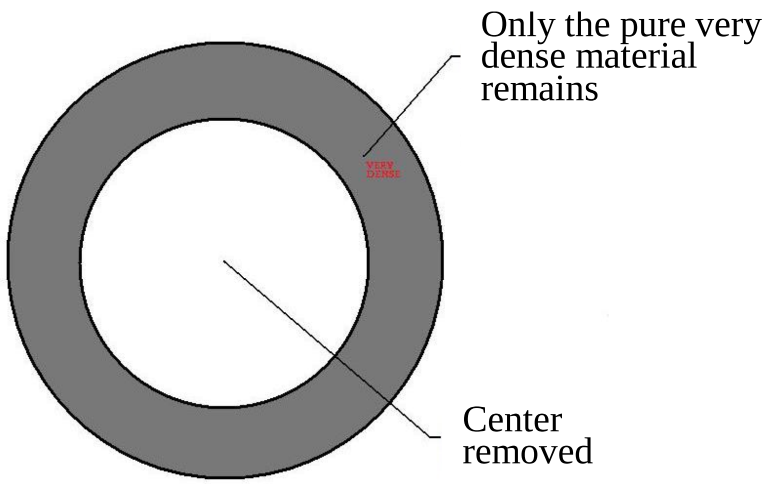


Figure 106 - Cast wheel

6.10. Centrifuge Casting

Centrifuge casting is the third main branch of centrifugal casting processes used for industrial manufacture of cast parts. For more detailed information on the other two manufacturing processes that fit into the category of centrifugal casting see, true centrifugal casting and semicentrifugal casting. Developing an understanding of these techniques will greatly assist in learning about centrifuge casting, since the main principles that govern centrifuge casting are the same for all centrifugal casting processes. Centrifuge casting is different in that castings manufactured by the centrifuge casting process need not have rotational symmetry. With centrifuge casting, metal castings of desired shapes can be manufactured with all the distinct benefits of castings produced by a centrifugal casting process.

The Process.

In centrifuge casting manufacture, molds employed to produce the desired castings are arranged around a central sprue. These molds contain all the necessary geometry for the cast part, as well as the gating system. Runners travel from the central sprue to the mold entrances.

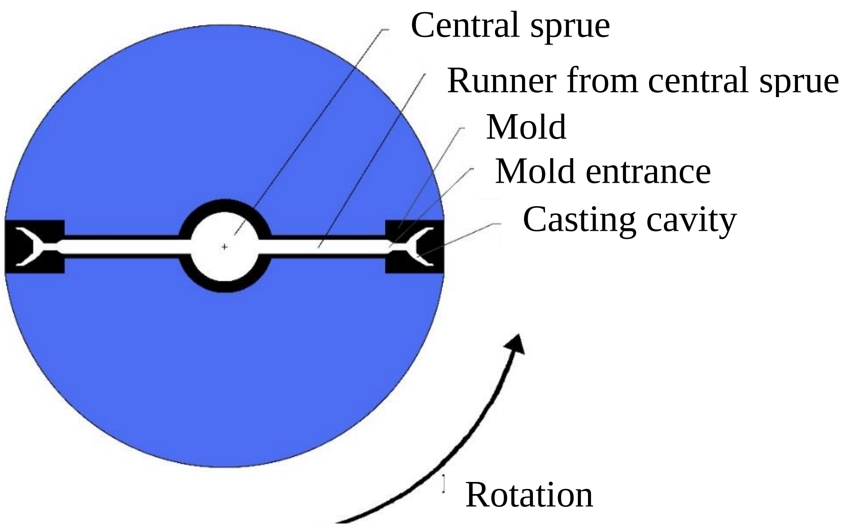


Figure 107 - Centrifuge casting (set up)

During the pouring phase of centrifuge casting manufacture, molten material is introduced into the central sprue. The entire system is rotated about an axis with the central sprue at the center of rotation. When an object is rotated, forces are produced that act directly away from the center of the axis of rotation. It would be known from the previous discussions concerning the other two branches of centrifugal casting, that the utilization of the forces of centripetal acceleration which act to push material away from the center of rotation is the trademark characteristic of all the manufacturing processes of centrifugal casting. Centripetal force is not only utilized to distribute molten material through a mold, but to help control the material properties of a cast part. In centrifuge casting manufacture, the molten material to produce the casting is poured into the central sprue. Centripetal forces from the rotating apparatus push this material outward from the center, through the runners and into the molds.

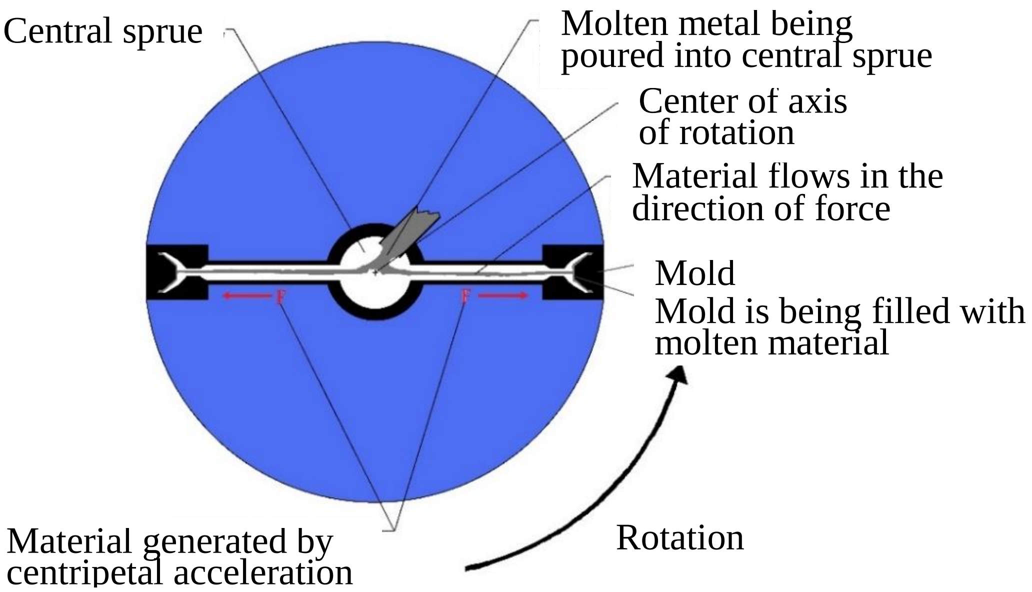


Figure 108 - Centrifuge casting (pouring)

When the correct amount of molten metal to manufacture the casting is poured and distributed completely into the molds, the apparatus will continue to rotate as solidification is occurring. After the castings have completely solidified, the apparatus will stop rotating and the parts can be removed.

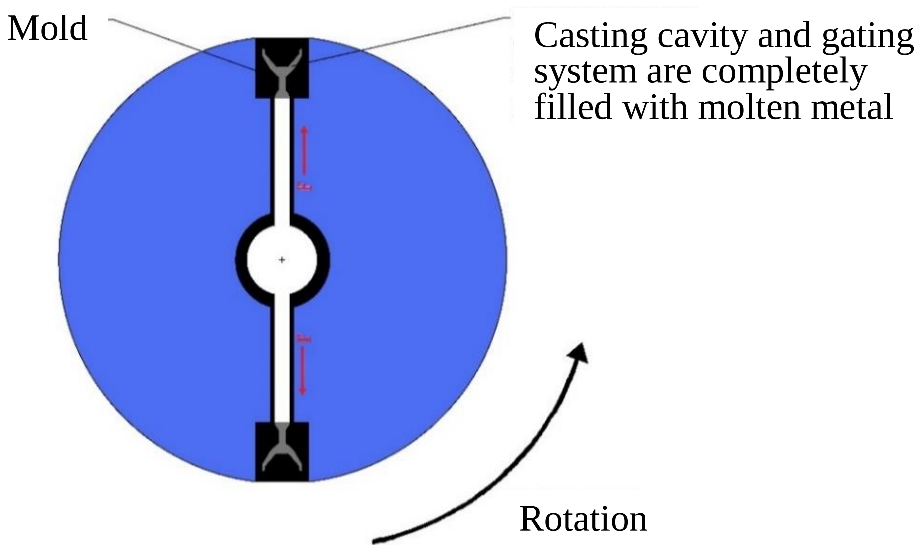


Figure 109 - Centrifuge casting (solidification)

Centrifuge Casting Manufacture.

There are many specific advantages in the quality of parts manufactured by centrifuge casting. Since the metal is forced into the mold, the mold cavity usually fills completely and cast parts with thin walled sections are possible. Also, great surfaces can be produced by centrifugal casting, which is another characteristic of castings manufactured by a process that uses large amounts of force to fill a mold.

One of the most notable features, specific to the centrifugal casting processes and discussed in the preceding sections, is the effect of centripetal forces acting continuously on the material as the casting solidifies. Molten material that solidified under greater force will be denser than the same material that solidified under less force. This can be observed in a round cylinder manufactured using the true centrifugal casting process.

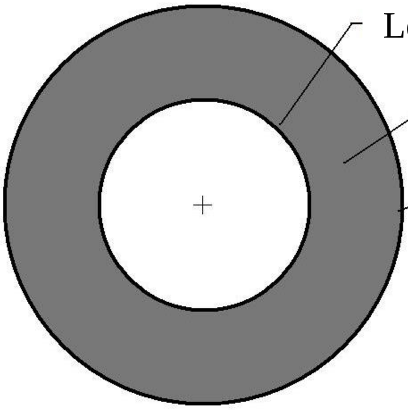


Figure 110 - Cast part produced by true centrifugal casting (i)

During the solidification of this part the mold was rotating. The forces acting on the material farther from the center were greater than the forces that were acting on the material closer to the center.

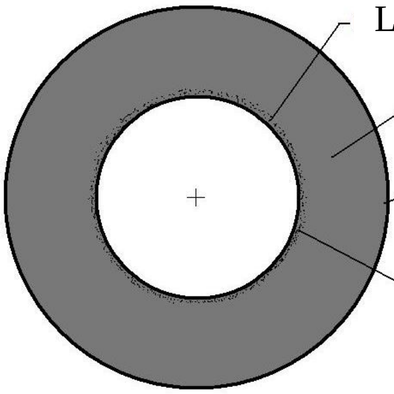


Figure 111 - Cast part produced by true centrifugal casting (ii)

Consequently, it can be seen in the manufactured part that the density is greatest in the outer regions and decreases towards the center.

Another specific effect that the centripetal forces used in centrifugal casting methods have on the material of a cast part is that impurities, such as inclusions and trapped air, tend to collect and solidify in the less dense material closer to the center of the axis of rotation.

This happens because the material itself is denser than these impurities, when subject to centripetal forces the denser metal pushes to the outer regions, forcing the lighter impurities to the less dense inner regions. These effects of centripetal forces on a casting can be observed not only in cast cylindrical tubes but also in all the wide variety of parts that can be manufactured using the centri fuge casting process as well.

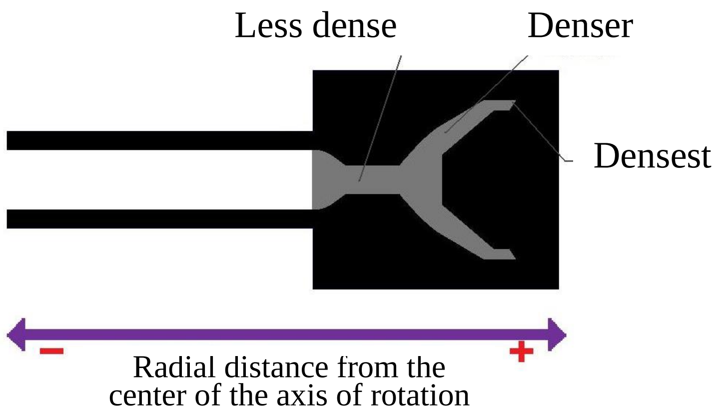


Figure 112 - Effects of centripetal forces

It can be seen that the density of the material varies throughout the cast part. The least dense section of the part will be the section that was closest to the center of rotation. The density of the material of the casting will increase with increasing radial distance from the center. Also, impurities that were present in the metal will have collected in the areas of the casting closest to the center of rotation.

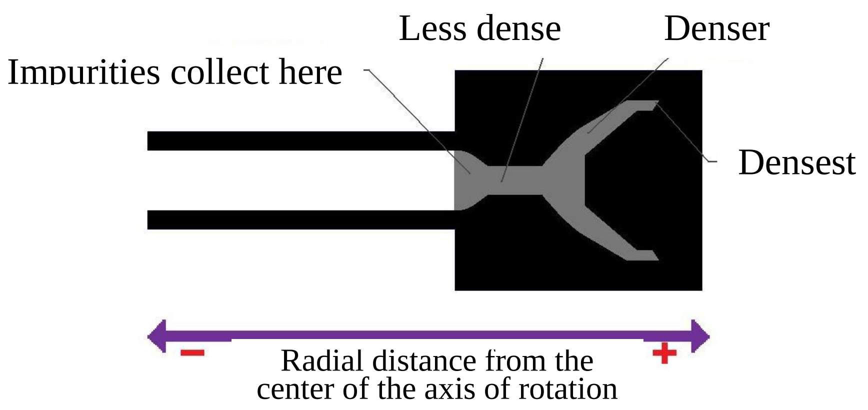


Figure 113 - Effects of centripetal forces

In a carefully planned centrifuge casting operation, the cast part can be designed to be manufactured in such a way that the less dense region containing the inclusions is removed after the production of the casting. This will create a finished part of pure, dense material.

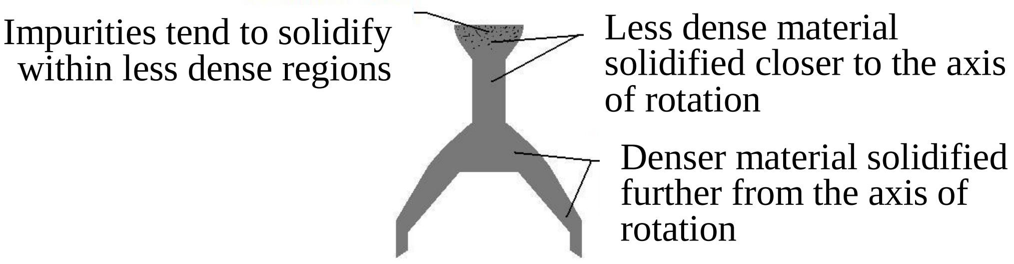


Figure 114 - Casting removed from mold

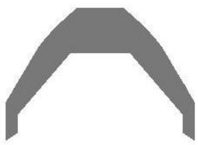


Figure 115 - Final manufactured cast part of only pure dense material

6.11. Ingot manufacture

Manufacturing by its nature involves the conversion of raw material to useful structures of certain geometry. There are many types of raw materials and they come in many forms. All materials in their most basic state are in some way obtained from the Earth. Most metals are not simply found in the state that we use them in everyday life. Rather they must be processed to create the desired material. The manufacture of most metals into a raw useful material state is a well developed process.

Typically the final result is a quantity of molten metal with the desired material consistency. The molten metal is usually either poured into large molds of basic shape, ingots, or fed into a continuous casting system. Continuous casting manufacture has the advantage of a higher rate of production, also raw metal produced can be cut into different desired lengths. A continuous casting operation can increase industrial efficiency by being fed directly into a rolling operation. Ingot casting manufacture is a more time consuming process since it requires large molds to sit and solidify. Ingot manufacture, however, can produce very large raw form castings, and requires much less manufacturing complication than continuous casting.

Ingots are commonly round, square, or rectangular in shape. Each ingot constitutes a certain amount of metal. Numbers of ingots of know mass may be used to quantify material requirements. Often ingots may be transported over distances to move to the next manufacturing plant. Ingots vary in size from a few hundred pounds to 355 tons. Enormous ingots are produced for the unique manufacture of especially massive parts, such as turbine rotors.

A casting melt in steel making industry typically weighs around 300 tons. While not that commonly produced an ingot weighing 300 tons would take an entire casting melt. Many ingots are usually poured with each melt. Normally ingots poured are under 40 tons. Some ingot are remelted for particular casting operations, but most are subject to subsequent metal forming manufacture.

A large consideration in the process of ingot manufacture is in the solidification of the part. Ingots usually take many hours to harden, the larger the ingot's mass the longer the solidification time. The outside surface of an ingot mold may be corrugated in order to speed heat loss and cooling rate. The ingot solidifies from the outside progressing towards the center and thus the ingot's grain structure develops as columnar and pointing in the direction of solidification. This grain structure development is typical of cast materials.

Due to long hardening times ingots tend to also develop grains that are large in size. The corners of the ingot's mold are rounded in order to avoid planes of weakness corners may cause particularly with regard to the columnar grain structure of castings. Shrinkage and gases liberated from the operation will cause a cast ingot to contain porosity and vacancies both large and small within the material. Large piping defect is cut from the casting, but most porosity in an ingot is acceptable, since it will be removed through further processing.

The majority of ingots are hot rolled as the next step after being cast. Hot rolling will break up the large columnar cast grain structure and reform a smaller more uniform wrought grain structure. As hot rolling breaks down the grain boundaries it pushes material, closing up and eliminating vacancies and porosity. Hot rolling further improves the quality of the ingot's material by also breaking up solid inclusions and distributing their material throughout the mass of the part.

Different molds may be used to produce ingots. The huge size of the mass of material that is solidifying makes vacancy due to shrinkage a particular problem in this process. Some molds may contain risers on the top or even gating systems to compensate for shrinkage. A very common ingot mold type used in manufacturing industry, particularly in steel making is the big end down mold.

This simple mold does not contain any risers or gating system, and can be quite large. The big end down mold is square, round, or rectangular, usually made of high carbon iron, tapered from top to bottom, and sits on a base. The ingot is poured and allowed to harden. Once the casting is solid the taper allows for the mold to be lifted from the base where the ingot remains.

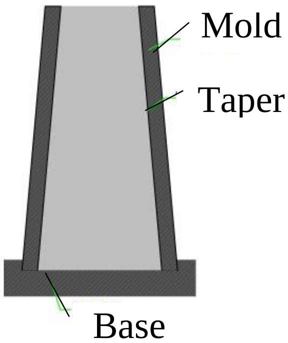


Figure 116 - Big end down mold

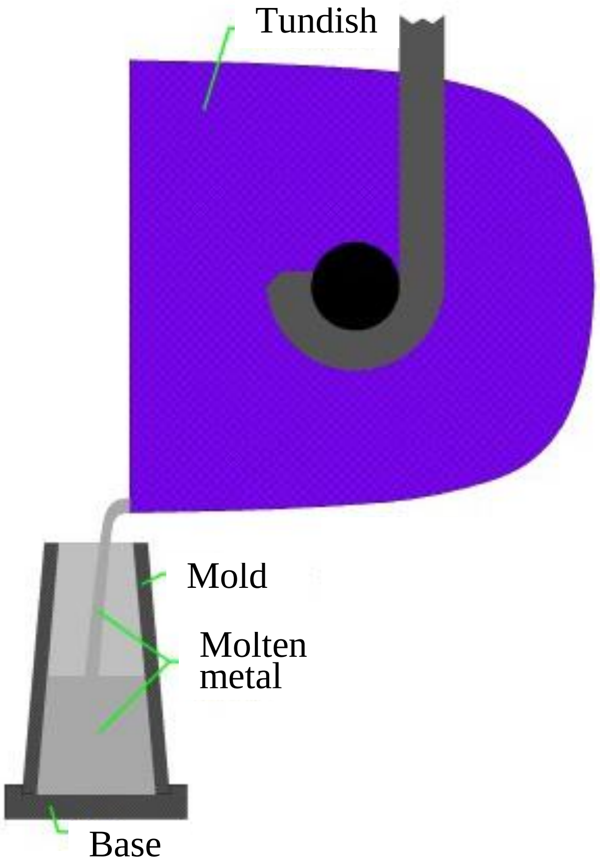


Figure 117 - Pouring of an ignot

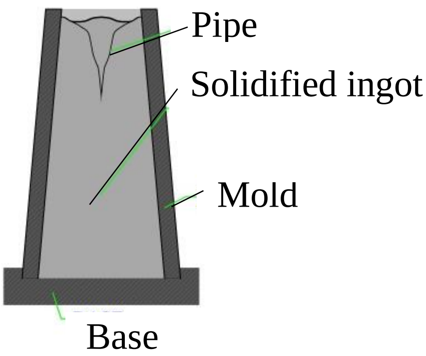


Figure 118 - Solidification of a cast ingot

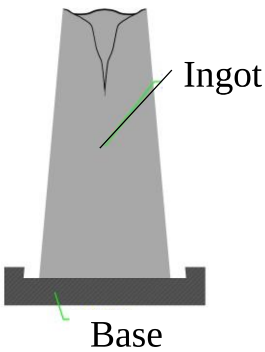


Figure 119 - Mold is lifted off leaving ingot on base

Steel production.

Steel is a fundamental and necessary part of our world. Steel comprises much of our physical civilization. The production of steel is of great importance and methods of steelmaking have been studied and refined over time. Both demand for and production of steel have also increased over time. Currently hundreds of millions of tons of steel are produced in the world each year.

Steel ingots are of three basic types rimmed, semi-killed, and killed. Gases, particularly oxygen, trapped in the molten metal are released as the material hardens. This is facilitated by an extreme decrease in the materials solubility limit as its temperature decreases. Oxygen combines with carbon and forms carbon monoxide. Gases may not escape the melt and form spherical vacancies within the material that remain upon solidification of the steel ingot.

In order to deoxidize the steel before it starts to solidify, different elements such as silicon, vanadium, manganese, and aluminum are added to the molten metal. These elements will react readily with oxygen, forming metallic oxides. Metallic oxides float in the melt and can be removed with the slag. The three basic types of steel ingots produced in industry today, represent three different degrees to which the steel melt is deoxidized.

Rimmed steel, usually low carbon steel, is deoxidized to the least degree. In rimmed steel gases released during the process form spherical blow holes within the material, particularly along the outer rim. Impurities will tend to segregate more towards the center of the casting. Material flaws in rimmed steel due to impurities can be an issue.

The goal when producing rimmed steel is an ingot with a sound outer skin. Blow holes within the metal may be closed up in latter forming processes. They are acceptable as long as they do not break through the outer skin, becoming exposed to the atmosphere. Rimmed steel has little piping if any, since the space taken by the gas pockets negates the space taken by shrinkage due to solidification.

Semi-killed steel is partially deoxidized by the addition of oxygen combining elements. Since semi killed steel is not completely oxidized, gases still form in the melt and create blowholes. Gas porosity is much less than rimmed steel and is usually more prevalent in the upper portion of the ingot. A semi killed steel ingot may have a little bit of piping. The semi-killed manufacturing process is an economical method of creating steel ingots.

Killed steel is produced by the full oxidation of the metal melt. Enough oxygen combining elements are added to the melt that the formation of metal oxides eats up all of the oxygen preventing the development of gas. Metallic oxides can form solid inclusions or combine with the slag, and can be scooped out with or along side it. The molten steel will sit quietly when the ingot is poured, hence the name killed. Killed steel has excellent chemical and mechanical properties that are uniform throughout the material. This high quality steel is free of porosity and blow holes. A killed steel ingot does not compensate for shrinkage through porosity and hence will develop a large pipe. The pipe of a killed steel ingot is usually cut off for scrap.

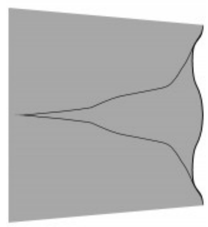


Figure 120 - Pipe

Advanced refining techniques.

In modern manufacturing industry their is a large demand for higher quality metals. Parts that serve critical applications should be assured not to fail due to flaws in material. Service life of most parts subject to stresses can be increased with the use of better grade metal. Different additives and secondary refining of molten metal is used in industrial processes to manufacture purer metal. The purer the metal, the higher will be its quality. Cleaner metals have better mechanical properties that will be consistent throughout the part. Melting and processing in a vacuum, controlled atmospheres, and inert gas are all used in various advanced refining techniques to produce superior melts.

6.12. Continuous casting

Continuous casting, also referred to as strand casting, is a process used in manufacturing industry to cast a continuous length of metal. Molten metal is cast through a mold, the casting takes the two dimensional profile of the mold but its length is indeterminate. The casting will keep traveling downward, its length increasing with time. New molten metal is constantly supplied to the mold, at exactly the correct rate, to keep up with the solidifying casting. Industrial manufacture of continuous castings is a very precisely calculated operation. Continuous casting can produce long strands from aluminum and copper, also the process has been developed for the production of steel.

The process.

Molten metal, from some nearby source, is poured into a tundish. A tundish is a container that is located above the mold, it holds the liquid metal for the casting. This particular casting operation uses the force of gravity to fill the mold and to help move along the continuous metal casting. The tundish is where the operation begins and is thus located high above ground level, as much as eighty or ninety feet. As can be seen, the continuous casting operation may require a lot of space.

It is the job of the tundish to keep the mold filled to the right level throughout the manufacturing operation. Since the metal casting is constantly moving through the mold, the tundish must always be supplying the mold with more molten metal to compensate.

The supplying of metal to the mold is not only going on throughout the entire manufacturing operation, it must be carried out with accuracy. A control system is employed to assist with this task. Basically the system can sense what the level of molten metal is, knows what the level should be, and can control the pouring of the metal from the tundish to ensure the smooth flow of the casting process. Although the tundish can typically hold several thousand pounds of metal, it too must be constantly supplied from the source of molten material.

The tundish also serves as the place where slag and impurities are removed from the melt. The high melting point and reactive nature, at high temperatures, has always made steel a difficult material to cast. When a manufacturing operation is continuously casting steel, the reactivity of the molten steel to the environment needs to be controlled.

For this purpose, the mold entrance may be filled with an inert gas such as argon. The inert gas will push away any other gases, such as oxygen, that may react with the metal. There is no need to worry about the inert gas reacting with a molten metal melt, since inert gases do not react with anything at all.

The metal casting moves quickly through the mold, in the continuous manufacture of the metal part. The casting does not have time to solidify completely in the mold. As can be remembered from our discussion on solidification, a metal casting will first solidify from the mold wall, or outside of the casting, then solidification will progress inward. The mold in the continuous casting process is water cooled, this helps speed up the solidification of the metal casting. As stated earlier, the continuous casting does not completely harden in the mold. It does, however, spend enough time in the water cooled mold to develop a protective solidified skin of an adequate thickness on the outside.

The long metal strand is moved along at a constant rate, by way of rollers. The rollers help guide the strand and assist in the smooth flow of the metal casting out of the mold and along its given path. A group of special rollers may be used to bend the strand to a 90 degree angle. Then another set will be used to straighten it, once it is at that angle. Commonly used in manufacturing industry, this process will change the direction of flow of the metal strand from vertical to horizontal.

The continuous casting can now travel horizontally as far as necessary. The cutting device, in manufacturing industry, is typically a torch or a saw.

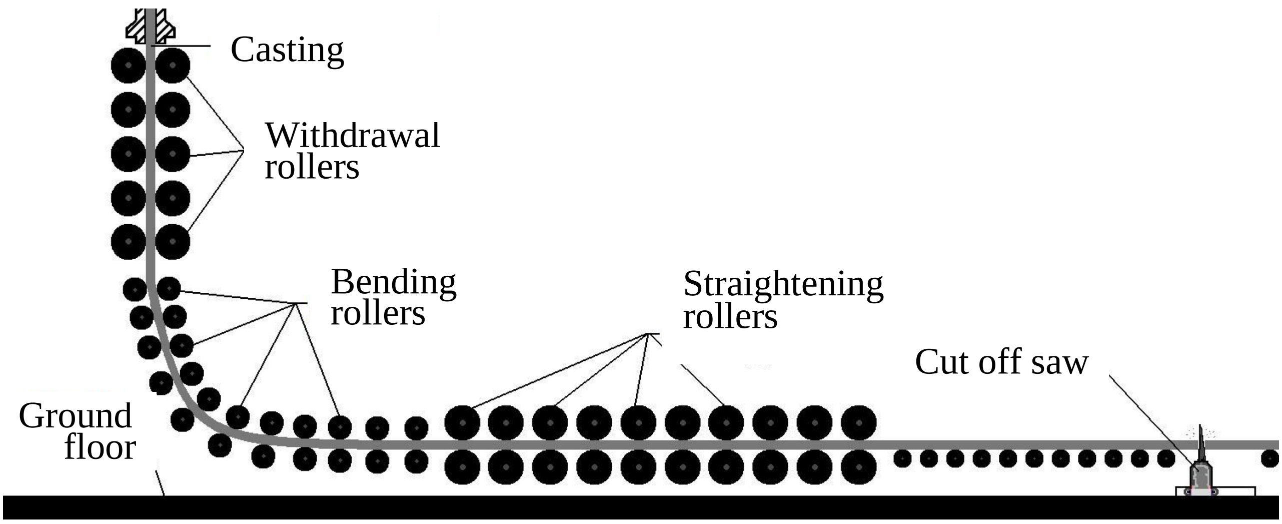


Figure 121 - Vertical to horizontal direction change for continuous casting manufacture

Since the metal casting does not stop moving, the cutting device must move with the metal casting, at the same speed, as it does its cutting. There is another commonly used setup for cutting lengths of metal casting strand from a continuous casting operation. This particular manufacturing setup eliminates the need for bending and straightening rollers. It does, however, limit the length of metal casting strand that may be produced, based in a large part on the height of the casting floor where the mold is located.

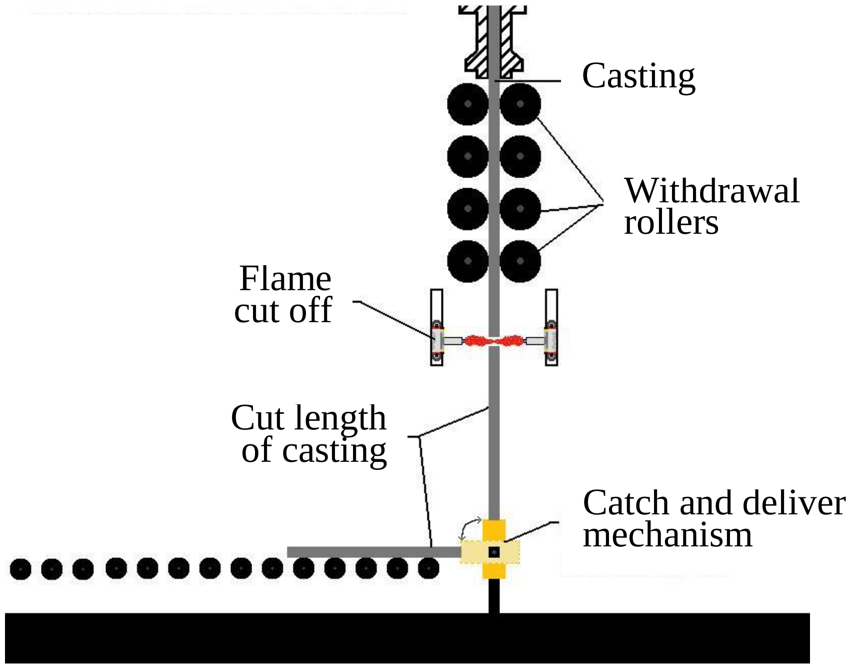


Figure 122 - Alternate method of cutting slabs for continuous casting manufacture

There needs to be an initial setup for a continuous casting operation, since you can not just pour molten metal through an empty system to start off the process. To begin continuous casting manufacture, a starter bar is placed at the bottom of the mold. Molten material for the metal casting is poured into the mold and solidifies to the bar. The bar gives the rollers something to grab onto initially. The rollers pull the bar, which pulls along the continuous casting.

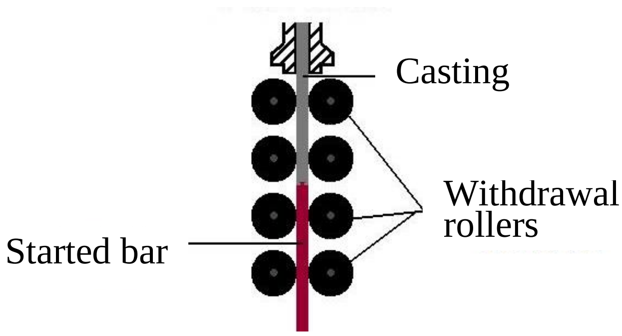


Figure 123 - Starting a continuous casting manufacturing process

In the manufacture of a product, often two or more different kinds of operations may need to be performed. Such as a metal casting operation followed by a metal forming operation. In modern commercial industry, the continuous casting process can be integrated with metal rolling. Do not confuse the rolling operation with the rolls used to guide the casting. The rolling operation is a forming process and it will change the metal it processes. Rolling of the metal strand, is the second manufacturing process and it must be performed after the casting operation. Continuous casting is very convenient in that the rolling mill can be fed directly from the continuously cast metal casting strand. The metal strand can be rolled directly into a given cross sectional shape such as an I beam. The rate of the rolling operation is synchronized with the speed that the continuous metal casting is produced and thus the two operations are combined as one.

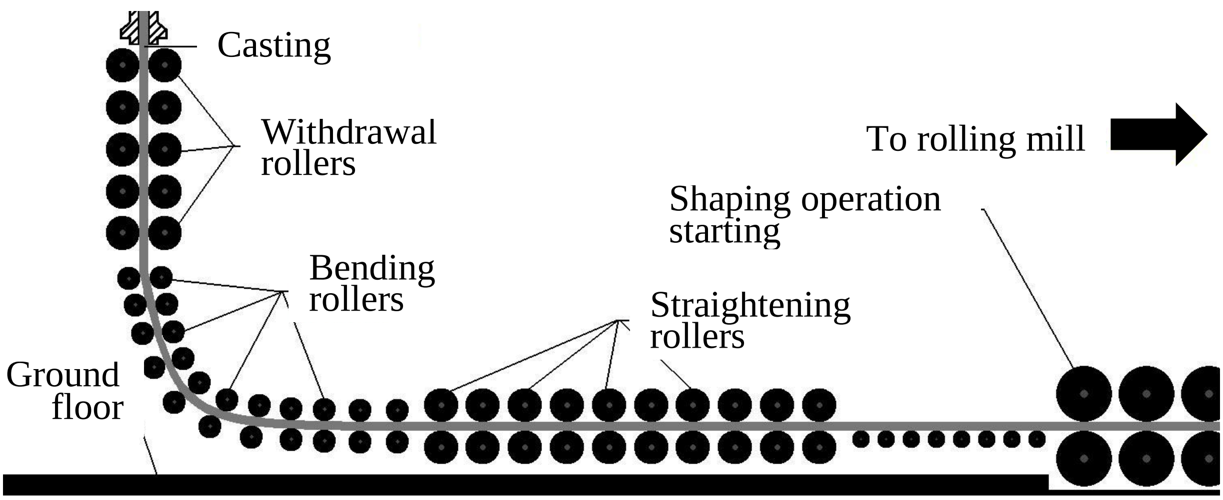


Figure 124 - Continuous casting combined with a rolling operation

Properties and considerations of manufacturing by continuous casting:

- Continuous casting manufacture is different from other metal casting processes, particularly in the timing of the process. In other casting operations, the different steps to the process such as the ladling of metal, pouring, solidification, and casting removal all take place one at a time in a sequential order. In continuous casting manufacture, these steps are all occurring constantly and at the same time.
- This process is used in commercial manufacture as a replacement to the traditional process of casting ingots.
- Piping, a common problem in ingot manufacture, is eliminated with the continuous casting process.
- Structural and chemical variations in the metal of the casting, often present in ingots, have been eliminated. When manufacturing with the continuous metal casting process, the casting's material will possess uniform properties.
- When employing continuous metal casting manufacture, the castings will solidify at 10 times the rate that a casting solidifies during ingot production.
- With less loss of material, cost reduction, higher productivity rate, and superior quality of castings, continuous casting manufacture is often the choice over ingot production.
- A continuous casting manufacturing process will take considerable resources and planning to initiate, it will be employed in only very serious industrial operations.

7. CASTING DEFECTS

Casting is a manufacturing process, in which a hot molten metal is use to poured into a mold box, which contains a hollow cavity of the desired shape, and then allowed to solidify. That solidified part is known as a casting, Casting is most often used for making complex shapes that would be otherwise difficult or uneconomical to make by other methods. Casting is a process which carries risk of failure occurrence during all the process of accomplishment of the finished product.

Casting process is associated with some casting defects that degrade the quality of foundry product. To upgrade the productivity of the organization the casting defects should be minimized.

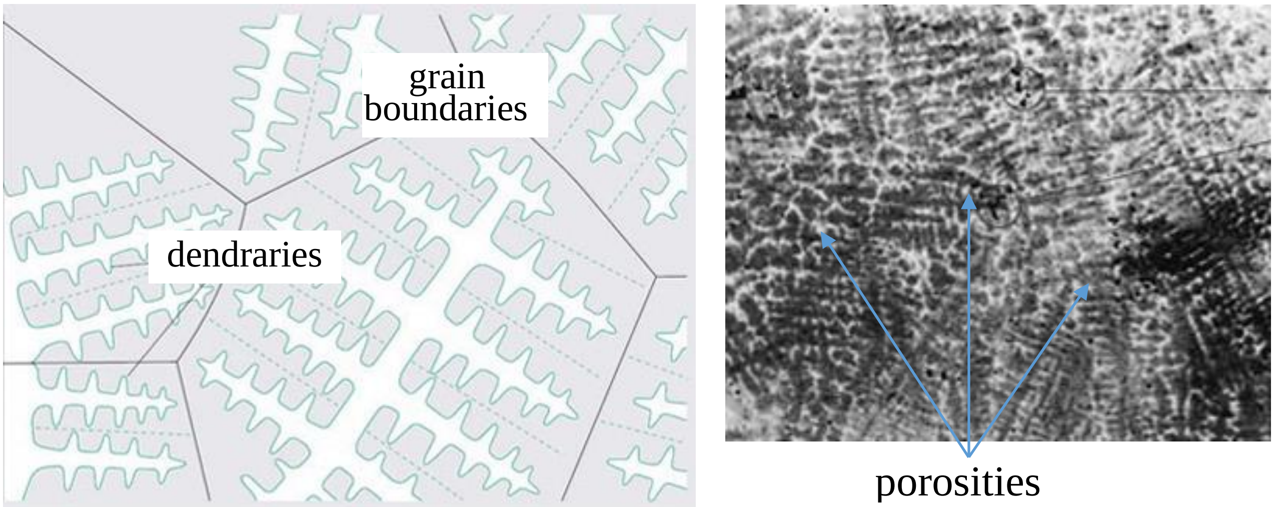
Hence necessary action should be taken while manufacturing of cast product so that defect free parts are obtained. During the process of casting, there is always a chance where defect will occur. A defect may arise due to a single cause or may be due to presence of some more causes it depends on foundry shop and its resources available. Minor defect can be adjusted easily but high rejected rates could lead to significant change at high cost. Therefore it is essential for die caster to have knowledge on the type of defect and be able to identify the exact root cause, and their remedies.

In a casting process, the material is first heated to completely melt and then poured into a cavity of the mold. As soon as the molten metal is in the mold, it begins to cool. When the temperature drops below the freezing point (melting point) of the material, solidification starts. Solidification involves a change of phase of the material and differs depending on whether the material is a pure element or an alloy. A pure metal solidifies at a constant temperature, which is its melting point (freezing point).

7.1. Casting microstructure and defects

Metal castings have very specific microstructures. When a liquid metal cools and begins to solidify in a mold, grains (crystals) of the metal start to form, both on the mold walls and in the bulk of the liquid metal. The way they grow is shown schematically in fig. 125 (a).

As the metal solidifies, it forms curious tree-like dendrites. This structure is maintained after the casting is fully solidified, as can be seen from fig. 125 (b), which shows a typical casting microstructure. The image is created by polishing the surface of the metal, immersing it for a short while in a dilute acid and viewing it under an optical microscope. In addition to the dendritic structure, there are two other common defects that can be found in a cast microstructure: particles of impurities known as inclusions, and porosity which is small holes in the casting.



a) b)

Figure 125 - Castings (a) dendritic formation (b) a typical cast microstructure

Some inclusions can be removed by heating the casting to a temperature somewhat below its melting point to anneal it and 'dissolve' the inclusions in the metal but the porosity is more difficult to remove. The porosity occurs because the casting has shrunk on solidification. Most materials contract on solidification (water is one of the few liquids that expands on solidification, so that ice floats on water; bad news for the titanic, but good news for polar bears) and this shrinkage is not always uniform, so that substantial holes and voids can be left in the casting.

This reduces the load-bearing capability of the component, and in highly stressed products, where the full strength of the material is being utilised, voids can lead to failure. The shrinkage on solidification can be large, and is generally a greater effect than the thermal contraction of the solid material as it cools to room temperature.

In many casting processes, runners and risers are used as reservoirs of molten metal to prevent voids from developing in the casting as it solidifies. The runners and risers are parts of the casting that contain a 'reserve' of extra liquid to feed into the mold as the cast product contracts during cooling.

However, if a volume of liquid material becomes surrounded by solid material, then a void is formed when the liquid solidifies and contracts.

Fig.126 shows a section through a gravity-die casting in which the effects of this contraction can be seen. The chimney-like feature is the runner, down which liquid aluminium alloy was poured into the mold. There is a hollow in the top of the runner caused by liquid flowing from the runner into the mold as the casting solidified. As well as the hollow at the top, you can see some holes in the runner and one hole within the casting itself. The runners and risers will later be cut off and discarded.

Fig. 126 - Section through a gravity die-cast microscope body

When we are using casting to form the final shape of a product, we have to live with the microstructure of our casting, including its defects. But if we are casting ingots to produce sheet or bar metal for further processing, then a mixture of large deformations and high temperatures is typically used to 'break down the cast structure, remove the porosity, and create a far more uniform microstructure. Such material is the typical raw material for the forming processes we will look at in the next section. Polymers do not produce the same cast microstructures as are seen in metals, as they are composed of long-chain molecules, rather than grains built up from an atomic lattice of metal atoms. However, polymers do shrink on solidification and in injection-molded products, shrinkage holes can form, particularly within thick sections.

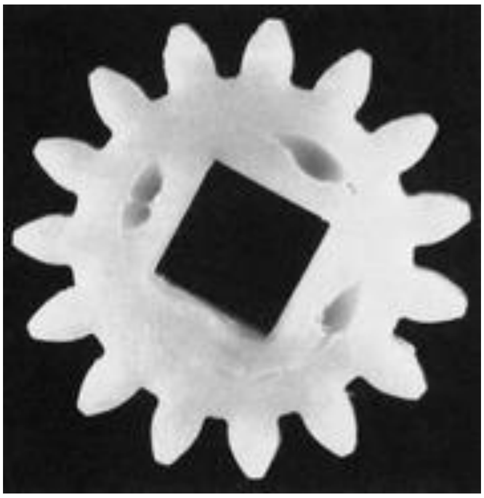


Fig. 127 - Section though a molded nylon gear showing three large shrinkage holes

Fig. 127 shows such holes in an injection-molded nylon gear. Alternatively, the contraction may take the form of depressions on the surface ('sink marks'). In an effort to 'feed' shrinkage holes with liquid, the pressure is maintained for a short time after the thermoplastic has been injected. Similar holes are found in pressure-die castings.

7.2. Casting defects and remedies

The undesired irregularity in a metal casting process is called casting defect. Casting defects may be defined as characteristics which create a deficiency or imperfection to quality specification imposed by design and service requirement. Casting defects are caused by non optimized process, failure of material, casting equipment (Table 3). So the defects can be tolerated and repaired. The three general origins of defects are:

1. Casting design.
2. Technique of manufacture or the method.
3. Application of technique- workmanship.

Categories of defects are the following:

1. Shaping faults in pouring.
2. Inclusions and sand defects.
3. Gas defects.
4. Shrinkage defects.
5. Contraction defects and
6. Dimensional defects.
7. Compositional errors.
8. Segregation.

A properly designed casting, a properly prepared mould and correctly malted metal should result in a defect free casting. However, if proper control is not exercised in the foundry-sometimes it is too expensive. Casting defect can be also classified as follows:

1. Filling related defects.
2. Shape related defects.
3. Thermal related defects.

1. Filling related defects.

Blowhole.

During solidifying metal on surface of metal a rounded or ovel shape hole cavity on smooth or clean surface which is associated with oxides. It collects into a bubble at the high points of a mold cavity ad prevents the liquid metal from filling that space. Blowhole is a kind of cavities defect, which is also divided into pinhole and subsurface blowhole. Pinhole is very tiny hole. Subsurface blowhole only can be seen after machining. The defects are nearly always located in the cope part of the mold in poorly vented pockets and undercuts.

Inclusions.

Inclusions are due to the presence of forging, non metallic particles in cast metal. These are may in the form of oxides, slag, dirt, sand or nails. These inclusion can limit mechanical properties and fatigue performance as well as lead to cosmetic defects.

Sand inclusion is nothing but a sand hole or blacking scab, it looks like small or middle holes with sand grain in the internal or on the surface of castings. Inclusion defects looks like there are slag inside of metal castings. Sand inclusions are one of the most common casting defects. This casting defect is formed during abrasion of the mold surface by the metal flowing past and the associated thermomechanical stresses.

The considerable compressive and shear stresses acting on the mold and core sections can lead to breakage of individual sand grains (erosions) or tearing off of larger mold sections (erosion scabs). This causes interruptions in smooth mold and core surfaces, thickening zones on individual casting sections and sand crusts (sand inclusions) in remote casting areas. Irregularly formed sand inclusions, it is often difficult to diagnose, as these defects generally occur at widely varying positions and are therefore very difficult to attribute to a local cause. Areas of sand are often torn away by the metal stream and then float to the surface of the casting because they cannot be wetted by the molten metal. Sand inclusions can also be trapped under the casting surface in combination with metal oxides and slag‘s, and only become visible during machining.

Cold lap or cold shut.

A cold shut is caused when two streams while meeting in the mold cavity, do not fuse together properly thus forming a discontinuity in the casting. When the molten metal is poured into the mold cavity through more-than-one gate, multiple liquid fronts will have to flow together and become one solid. If the flowing metal fronts are too cool, they may not flow together, but will leave a seam in the part. Such a seam is called a cold shut, It is a crack with round edges. Cold lap is because of low melting temperature or poor gating system. When the metal is unable to fill the mold cavity completely and thus leaving unfilled portion called misrun. A cold shunt is called when two metal streams do not fuse together properly.

Misrun.

Misrun defect is a kind of incomplete casting defect, which causes the casting uncompleted. The edge of defect is round and smooth. When the metal is unable to fill the mold cavity completely and thus leaving unfilled portion called misrun. A cold shunt is called when two metal streams do not fuse together properly.

Porosity.

Porosity in castings is due to bubbles being trapped during solidification. Porosity describes the presence of voids inside casting of different size, shapes, surface constituents. Porosity can be divided into two types: gas porosity and shrinkage porosity. The gas can be from trapped air, hydrogen dissolved in aluminum alloys, moisture from water based die lubricants or steam from cracked cooling lines, usually internal, caused by trapped gases of various kinds in the die. Gas porosity comes from three main sources in die-casting, namely trapped air steam and burned lubricant.

Air is present in the cavity before the shot. It can easily be trapped as the metal starts to fill the cavity. The air is then compressed as more and more metal streams into the cavity and the pressure rises. When the cavity is full it becomes dispersed as small spheres of high pressure air. The swirling flow can cause them to become elongated.

Shrinkage porosity is one of the most common defects to rejection of metal casting. It can be described as internal cracks in casting which comes from several sources.

Sinks.

Sinks form when there is presence of sub-surface cavity. A sink is depression impacting of surface of part that does not mimic the mould surface. Sinks are often visible because they reflects light.

2. Shape defects.

Blister.

In blister the thin film of small surface blows up from the part surface when the internal pressure of surface gas related porosity plastically deforms the metallic surface. Blister represents an example of defect of metallurgical defects.

Mismatch defect.

Mismatch in mold defect is because of the shifting molding flashes. It will cause the dislocation at the parting line.

Distortion or warp.

Warped casting—distortion due to warp age is known as warp defect.

Flash defect.

Flash can be described as any unwanted, excess metal which comes out of the die attached to the cavity or runner. Typically it forms a thin sheet of metal at the parting faces. There are a number of different causes of flash and the amount and severity can vary from a minor inconvenience to a major quality issue. At the very least, flash is waste material, which mainly turns into dross when re-melted, and therefore is a hidden cost to the business.

Segregation.

Segregation occurs due change in chemical composition of metal. Segregation is distinguish between two types: micro segregation and macro segregation. Micro segregation refers to localize difference between dendrite arm. Distance involved is about 10 to 100µm which is small for diffusion to be significant mechanism and this is not in case of micro seggregation.

Mechanically induced defects.

Mechanically induced defects such as surface marks, undercuts and bending occurs during ejection of casting and due to insufficient draft angle. Under cuts are formed due to erosion of sand by the stream of molten metal. It shows the pattern around the gates and causes dirt in casting. Bending and surface marks are caused by external pressure loads, improper ejection methods. These defects can be avoided by giving proper draft angle and using standard ejection methods and modified casting designs.

3. Thermal defects.

Cracks or tears.

Cracks can appear in die castings from a number of causes. Some cracks are very obvious and can easily be seen with the naked eye. Other cracks are very difficult to see without magnification.

Shrinkage.

Shrinkage defects occur when feed metal is not available to compensate for shrinkage as the metal solidifies. Shrinkage defects can be split into two different types: open shrinkage defects and closed shrinkage defects. Open shrinkage defects are open to the atmosphere, therefore as the shrinkage cavity forms air compensates. There are two types of open air defects: pipes and caved surfaces. Pipes form at the surface of the casting and burrow into the casting, while caved surfaces are shallow cavities that form across the surface of the casting.

Closed shrinkage defects, also known as shrinkage porosity, are defects that form within the casting. Isolated pools of liquid form inside solidified metal, which are called hot spots. The shrinkage defect usually forms at the top of the hot spots. They require a nucleation point, so impurities and dissolved gas can induce closed shrinkage defects. The defects are broken up into macro porosity and micro porosity (or micro shrinkage), where macro porosity can be seen by the naked eye and micro porosity cannot.

Soldering.

Soldering is one of the main and major casting defects in metal die casting process. Soldering occurs when molten metal sticks the surface of die steel and remain there after the ejection of casting. Soldering occurs after just few casting cycle.

Cold shut.

Cold shut forms when small droplets of metal fall into casting, mold. Solidify and fail to combine when remaining metal introduced to mold. Cold shut is crack with round edges. In cold shut two different metal stream do not forged together.

Defect by gating system.

A proper runner and gating framework are essential to secure quality of casting. With the use of casting simulation technique design of the gating framework of casting defect has been measured. In this manner, the casting simulation technique has become an essential tool for casting defect troubleshooting and optimization method. It helps in enhancing product quality and upgrade the yielding of casting, reduced cost and spare time among other optimization technique.

Careful control of large number of variables needed:

1. Characteristics of metals & alloys cast.
2. Method of casting.
3. Mold and die materials.

4. Mold design.
5. Process parameters - pouring, temperature.
6. Gating system.
7. Rate of cooling.

Design modifications to avoid defects are the following:

1. Avoid sharp corners.
2. Maintain uniform cross sections.
3. Avoid shrinkage cavities.
4. Use chills to increase the rate of cooling.
5. Stagger intersecting regions for uniform cross sections.
6. Redesign by making parting line straight.
7. Avoid the use of cores, if possible.
8. Maintain section thickness uniformity by redesigning.
9. Allowances for shrinkage to be provided.
10. Parting line to be along a flat plane-good at corners or edges of casting.
11. Draft to be provided.
12. Permissible tolerances to be used.
13. Machining allowances to be made.
14. Residual stresses to be avoided.
15. Large flat areas to be avoided- warping due to temperature gradient.

Examples of the most commonly casting defects, their causes and suggested remedies are presented in Table 4.

Table 3 - Probable causes and suggested remedies of casting defects

Name of casting defects	Probable causes	Suggested remedies
1	2	3
Blow holes	1. Excess moisture content in molding sand. 2. Rust and moisture on Chills, chaplets and inserts. 3. Cores not sufficiently baked. 4. Excessive use of organic binders. 5. Molds not adequately vented. 6. Molds not adequately vented. 7. Molds rammed very hard.	1. Control of moisture content. 2. Use of rust-free chills, chaplet and clean inserts. 3. Bake cores properly. 4. Ram the mold s less hard. 5. Provide adequate venting in mold and cores.
Strinkage	1. Faulty gating and risering system. 2. Improper chilling.	1. Ensure proper directional solidification by modifying gating, risering and chilling.
Porosity	1. High pouring temperature. 2. Gas dissolved in metal charge. 3. Less flux used. 4. Molten metal not properly degassed. 5. Slow solidification of casting. 6. High moisture and low permeability in mold.	1. Regulate pouring temperature 2. Control metal composition. 3. Increase flux proportions. 4. Ensure effective degassing. 5. Modify gating and risering. 6. Reduce moisture and increase the permeability of mold.
Misruns	1. Lack of fluidity ill molten metal. 2. Faulty design. 3. Faulty gating.	1. Adjust the proper pouring temperature. 2. Modify design. 3. Modify gating system.

Continue Table 3

1	2	3
Hot Tears	1. Lack of collapsibility of core. 2. Lack of collapsibility of mold. 3. Faulty design. 4. Hard Ramming of mold.	1. Improve core collapsibility. 2. Improve mold collapsibility. 3. Modify casting design. 4. Provide softer ramming.
Metal penetration	1. Large grain size and used. 2. Soft ramming of mold. 3. Molding sand or core has low strength. 4. Molding sand or core has high permeability. 5. Pouring temperature of metal too high.	1. Use sand having finer grain size. 2. Provide hard ramming. 3. Suitably adjust pouring temperature.
Cold shuts	1. Lack of fluidity in molten metal. 2. Faulty design. 3. Faulty gating.	1. Adjust the proper pouring temperature. 2. Modify design. 3. Modify the gating system.
Cuts and washes	1. Low strength of mold and core. 2. Lack of binders in facing and core sand. 3. Faulty gating.	1. Improve mold and core strength. 2. Add more binders to the facing and stand. 3. Improve gating.
Inclusions	1. Faulty gating. 2. Faulty pouring. 3. Inferior molding or core sand. 4. Soft ramming of mold. 5. Rough handling of mold and core.	1. Modify the gating system. 2. Improve pouring to minimize turbulence. 3. Use of superior sand of good strength. 4. Provide hard, ramming.
Fusion	1. Low refractoriness in molding sand 2. Faulty gating. 3. Too high pouring temperature of the metal. 4. Poor facing sand.	1. Improve refractoriness of sand. 2. Modify the gating system. 3. Use lower pouring temperature. 4. Improve the quality of facing sand.

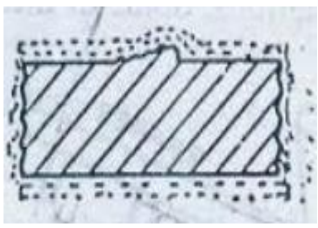
Continue Table 3

1	2	3
Drops	1. Low green strength in molding sand and core. 2. Too soft ramming. 3. Inadequate reinforcement of sand.	1. Increase green strength of sand mold. 2. Provide harder ramming. 3. Provide adequate reinforcement to and core projections sand projections and cope by using nails and gaggers.
Shot Metal	1. Too low pouring temperature. 2. Excess sulphur content in metal. 3. Faulty gating. 4. High moisture content in molding sand.	1. Use proper pouring temperature. 2. Reduce sulphur content. 3. Modify gating of system.
Shift	1. Worn-out or bent clamping pins. 2. Misalignment of two halves of pattern. 3. Improper support of core. 4. Improper location of core. 5. Faulty core boxes. and core 6. Insufficient strength of molding sand and core.	1. Repair or replace the pins, for removing defect. 2. Repair or replace dowels which cause misalignment. 3. Provide adequate support to core. 4. Increase strength of both mold.
Crushes	1. Defective core boxes producing over-sized cores. 2. Worn out core prints on patterns producing under sized seats for cores in the mold. 3. Careless assembly of cores in the mold.	1. Repair or replace the pins, for removing defect. 2. Repair or replace dowels which cause misalignment. 3. Provide adequate support to core. 4. Increase strength of both mold and core.
Hard Spot	1. Faulty metal composition. 2. Faulty casting design.	1. Suitably charge metal composition. 2. Modify casting design.

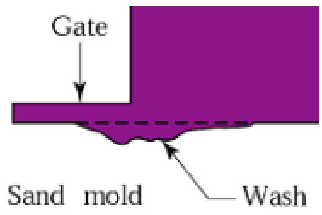
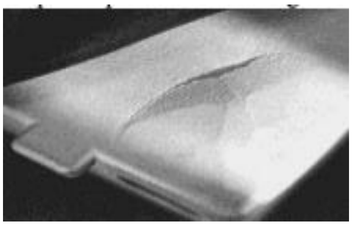
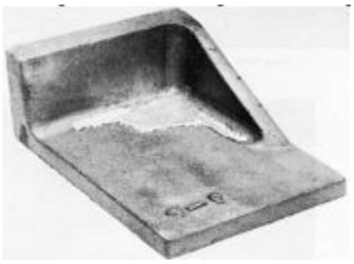
Continue Table 3

1	2	3
Swells	1. Too soft ramming of mold. 2. Low strength of mold and core. 3. Mold not properly supported.	1. Provide hard ramming. 2. Increase strength of both mold and core.
Rat-tails or buckles	1. Continuous large flat surfaces on casting. 2. Excessive mold hardness. 3. Lack of combustible additives in molding sand.	1. Break continuity of large flat groves and depressions. 2. Reduce mold hardness. 3. Add combustible additives to sand.
Run out, fins and fash	1. Faulty molding. 2. Defective molding boxes.	1. Improving molding technique. 2. Change the defective molding boxes. 3. Keep weights on mold boxes.
Spongings	1. Availability of dirt and swarf held in molten metal. 2. Improper skimming. 3. Because of more impurities in molten metal.	1. Remove dirt swarf held in molten metal. 2. Skimming should be perfect. 3. Fewer impurities in molten metal should be there.
Warpage	1. Continuous large flat surfaces on castings indicating a poor design. 2. No directional solidification of castings.	1. Follow principle of sufficient directional solidification. 2. Make good casting design.

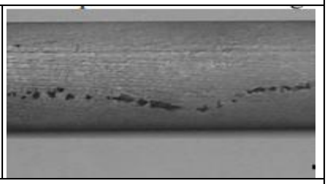
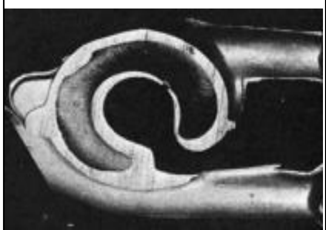
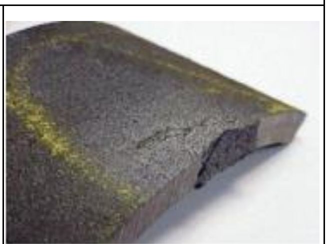
Table 4 – Examples of the most commonly casting defects

Features	Causes	Remedies	Example
1	2	3	4
Blow			
It is a largely well – rounded cavity produced by the gases which displace the molten metal at the cope surface of a casting. Generally occurs on the convex casting surface.	1. Excessive moisture content in the mold. 2. Rust and moisture in chill. 3. Cores are not sufficiently baked. 4. Excessive use of organic binder. 5. Mold rammed very hard.	1. Can be avoided by having a proper venting and adequa-te permeability. 2. Controlled content of moisture and volatile constituents in the sand – mix. 3. Ram the mold less.	
Pin Holes			
These are tiny blow holes. Occur either at or just below the casting surface.	1. Occurs due to gas dissolved in the alloy & the alloy not properly degasses.	1. Maintaining pouring temperature.	
Drop			
An irregularly – shaped projection on the cope surface of a casting is called drop.	1. By dropping of sand from the cope or other overhanging projections into the mold. 2. Inadequate of reinforcement of sand and core projection.	1. Adequate strength of the sand and the use of gaggers can avoid the drops. 2. Provide harder rammer. 3. Increase green strength of green sand.	
Dirt			
Sand particles dropping out of the cope get embedded on the top surface of the casting when removed leave small angular – holes.	1. Hydrogen in the molten metal.	1. Pattern should have little part as possible in the cope and the most critical surface should be placed in the drag.	

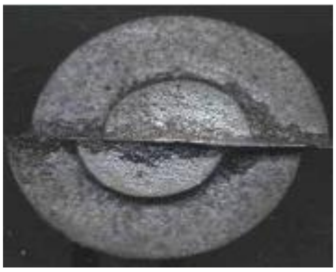
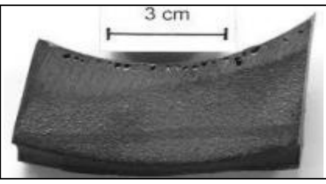
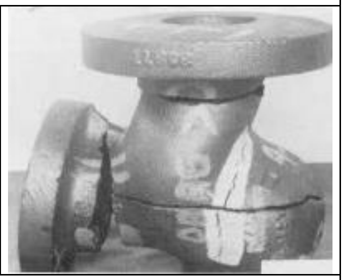
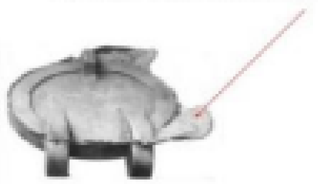
Continue Table 4

1	2	3	4
Wash			
Low projection on the drag surface commencing near the surface.	1. By the erosion of sand due to high velocity jet of liquid metal in the bottom gate. 2. Lack of binders in facing and core stand. 3. Low strength of mold and core.	1. Improve gating system. 2. Add more binders to facing and core sand.	
Bluckle			
Long, fairly shallow, broad, vee- shaped depression occurring in the surface of the flat casting.	1. Expansion of the thin layer of sand at the mold face takes place before the liquid metal at the mold face solidifies.	1. Proper amount of volatile additives in the sand–mix is essential to make room for this expansion and to avoid buckles.	
Scab			
Rough, thin layer of a metal, protruding above the casting surface on top of a thin layer of sand.	1. When the upheaved sand is separated from the mold surface and the liquid metal flows into the space between the mold and the displaced sand.	Lower the moisture content of the molding sand, which increases the overall mold strength. 2. Lower the pou-ring temperature of the metal (eliminate excess superheat), which reduces the amount of sand expansion. 3. Lower the temperature of the molding sand from the return sand system to increase the strength properties of the sand.	

Continue Table 4

1	2	3	4
Dross			
Lighter impurities appearing on the top surface of a casting.	1. Very high temperature. 2. Composition of molten metal.	1. Using strainer and skim bob at the pouring stage.	
Penetration			
Rough, porous projection on casting.	1. If the mold surface is too soft and porous the liquid metal flows between the sand particles up to the distance into the mold. 2. Large grain size. 3. Mold sand and core has low strength.	1. Suitable adjustable pouring temperature. 2. Sand having fine grain size. 3. Provide hard ramming.	
Swell			
Defect is found on the vertical surfaces of a casting.	1. Deformed by the hydrostatic pressure caused by the high moisture content in the sand. 2. Improper ramming of the mold.	1. Proper chose of riser.	
Misrun			
Insufficient filling of molten metal in mold cavity.	1. Due to insufficient superheat, material start freezing before reaching the farthest point of the mold cavity. 2. Faulty design and gating.	1. Adjust proper pouring temperature. 2. Improve design and gating system.	
Wrap			
Distortion due to warp age is known as warp defect.	1. Distortion due to warp age can occur over time in casting that partially or completely liberates residual stresses.	1. Common practice in iron casting is normalizing heat treatment to remove residual stress.	

Continue Table 4

1	2	3	4
Shift			
Misalignment between two halves of the mold.	1. Worn out or bend clamping pin. 2. Misalignment of two halves of patterns. 3. Improper support of core.	1. Repair or replace the support pins. 2. Provide adequate support to core. 3. Increase strength of both mold and core.	
Strinkage			
Reduction in required dimension.	1. Faulty gating and riser system. 2. Improper chilling.	1. Proper directional solidification by gating system, riser and chilling.	
Porosity			
Very small holes uniformly dispersed throughout casting.	1. Due to decrease in gas solubility during solidification. 2. High pouring temperature. 3. High moisture and low permeability. 4. Less flux used.	1. Control metal composition. 2. Increase flux proportion. 3. Reduce moisture and increase perme-ability of mold. 4. Effective degassing.	
Hot Tear			
A crack that develop in casting due to high residual stresses.	1. Lack of collap-sibility in mold. 2. Hard ramming of mold. 3. Lack of collapsibility in core.	1. Improve collapsibility of core and mold. 2. Modify casting design.	
Flash			
Flash is an excess material projecting from casting, generally visible as a thin metallic sheet, perpendicular to the casting face.	1. High pouring temperature. 2. Pattern having cavities as the end. 3. Improper clamping of top and bottom parts.	1. Ensure end cavi-ties to be filled to avoid metal leakage. 2. Dimensions to be controlled. 3. Sealing of mold box near parting line. 4. Proper core setting.	finds or flash 

8. COMPUTER SYSTEMS FOR CASTING PROCESSES SIMULATION

Foundry is the main base of the mechanical engineering and metallurgical complex, and its development depends on the pace of development of these industries as a whole. However, manufacturing cast parts with improved physical-chemical characteristics is a very important production task, which scientists and industrialists are aiming to solve.

Metallurgy and foundry are science-intensive, complex and interconnected industries. Metallurgists and foundry workers, in addition to the tasks of direct control of technological processes, in their activities are often faced with the need to perform rather complex technological and engineering-economical evaluations.

From the analysis of the current circumstance and prospects for the development of innovative technologies, it follows that to modernize the foundry, first of all, it is necessary to significantly increase the volume of investments in science: researches and development; design of new machines, equipment and technologies; development efforts, the acquisition of patents or licenses, software products; education and training. A whole range of technological solutions is needed to most effectively implement the priority areas.

Information technologies are such innovative technologies that can make the greatest contribution to accelerating economic growth and increasing the competitiveness of products. They are realized through computer design, an electronic archive, which contains all the information and from where it goes to the technologists, designers, and from them - to the design objects. At the same time, a large number of shortcomings in the organization of national production are revealed and there is an opportunity for their elimination [59].

At present, one of the main ideas for the development of industry should be neo-industrialization, which is a process of large-scale modernization based on waste-free technologies of automated, computerized, and robotic production [26].

The listed factors make it possible to define the main reference direction of the strategy for the further development of the foundry. These areas covered almost the entire range of problems of modern industrial production, namely [76]:

– the maintenance and development directions of the world and national foundry production;

– modern technologies, materials, and equipment;

– diagnostics, certification and quality management of castings;

– computer technologies in the foundry.

As seen from the above, one of the main strategic tendencies of the foundry at the present stage is the development of simulation and computer technologies.

Mathematical simulation of casting processes is the most effective, reliable, and widespread method of manufacturing casting technology development in the world, which allows reducing the costs of both process engineering and production of castings.

Computer analysis at the stage of virtual design of the casting technology (before the manufacture of castings) allows: to minimize possible miscalculations and errors that inevitably arise in the development process; to reduce financial and time costs; to increase efficiency, competitiveness, quality, and reliability of products being developed. There is a saving of materials, energy carriers, operating time, equipment is saved, and in return, a lot of unique information about the technological process is obtained. Only computer simulation of the technology allows to look inside the product and see the nature of the processes taking place in it, and understand the causes of defects.

The introduction of computer technologies also makes it possible to increase the efficiency of operations for creating and processing information - there is a real transition from paper to electronic document flow. At the same time, costs, the labor intensity of designing and mastering the production of new complex products are reduced. For example, the costs of preparing technical documentation are reduced by 30...40% and the lead time of the release of new complex products is reduced by more than 35% [26].

The development of simulation and computer technologies in foundry production involves:

– automated design of foundry technology;

– modeling the cast molding - a synthesis system for all elements of the process;

– design of foundry technology and tooling in a CAD system with its subsequent manufacture on CNC machines;

– development of a rapid prototyping system;

– computer control of technological equipment.

Computer programs for simulation the casting processes are designed to solve the following tasks:

– development of complex or essential casting technologies;

– determination of the parameters that are most important in influencing the quality and yield of suitable products;

– finding the causes of defects in already used technologies;

– determining the technology's resistance to changes in external parameters;

– searching for new technological solutions for obtaining complex castings.

The ability to correctly solve these problems acquires an important, and often decisive, competitive advantage. One of the reasons for this is that the use of computer modeling involves a high culture of design, modeling, and manufacturing.

Currently, dozens of different software products are used in the foundry production aimed at solving the problems facing the casting technologists. They differ in their characteristics, use various computational methods, mathematical algorithms and physical models, which, to varying degrees, satisfy the needs of a particular consumer. Only a comparison of the results of computer simulation with the results of industrial and experimental researches allows assessing the objectivity and adequacy of the software product used.

Today in the world there are a large number of programs for computer simulation of foundry processes. In world practice, the programs presented in Table 5 have received the main distribution.

Currently, in the USA, England, and Europe, the most common are two modeling systems: ProCast and MagmaSoft. In addition, a certain market segment in Europe is occupied by WinCast, SolidCast, and Nova-Solid/Flow systems. In Eastern Europe and the countries of the former CIS, the most popular software systems are Polygon and LVMFlow.

Modern programs for casting processes simulation are based on physical theories of thermal, diffusion, hydrodynamic, and deformation phenomena. They can adequately simulate many processes occurring during the filling of a mold with liquid metal, crystallization of a multi-component alloy, and further cooling of the casting.

Possibilities of the programs include hydrodynamic calculation of filling molds, analysis of temperature fields during crystallization and formation of shrinkage defects, calculation of stresses and residual deformations in castings, optimization of gating systems.

Table 5 - Casting simulation software [76]

<table>
<tr><th>Country-Vendor</th><th>Casting Simulation Software</th><th>Country-Vendor</th><th>Casting Simulation Software</th></tr>
<tr><td rowspan="2">Australia</td><td rowspan="2">CastFlow
Castherm</td><td>Japan</td><td>JSCAST</td></tr>
<tr><td>Korea</td><td>AnyCasting</td></tr>
<tr><td>China</td><td>InteCast</td><td rowspan="3">Russia</td><td rowspan="3">Polygon
LVMFlow
FlowVision</td></tr>
<tr><td>Finland</td><td>CastCAE</td></tr>
<tr><td rowspan="4">France</td><td rowspan="4">ProCast
QuikCast
PAM-Cast
CalcoSo</td></tr>
<tr><td>Spain</td><td>Vulcan</td></tr>
<tr><td>Sweden</td><td>Nova-Solid/Flow</td></tr>
<tr><td rowspan="4">USA</td><td rowspan="4">PowerCast
SolidCast
CAPCast
Flow3DCast
RAPIDCast</td></tr>
<tr><td>Germany</td><td>MagmaSoft
WinCast</td></tr>
<tr><td>Great Britain</td><td>MavisFlow</td></tr>
<tr><td>India</td><td>AutoCast</td></tr>
</table>

All programs mainly differ in purpose (Table 6), functionality, the number of simulated technological operations, the degree of completeness of the factors taken into account in the simulation, the equipment used. The main problems when choosing a specific program for modeling casting technological processes are the lack of reliable information about the capabilities of the program itself, the principles of working with it, as well as the absence of highly qualified specialists. A significant factor for national enterprises when choosing a program for modeling foundry processes is its cost.

The main distinguishing feature of software products is the used numerical method for solving problems of differential equations in simulation the cast molding (Table 7).

Table 6 – Casting processes simulated by selected software

Casting process	Auto Cast	CAP Cast	Cast CAE	Flow 3D Cast	Magma Soft	Nova Solid/ Flow	Pro Cast	Solid Cast	Poly-gon
Sand casting	+	+	+	—	+	+	+	+	+
High pressure die casting	—	+	+	+	+	+	+	—	+
Low pressure die casting	—	+	+	—	+	+	+	+	+
Continuous casting	—	—	—	+	—	—	+	—	—
Gravity die casting	+	—	+	+	+	+	+	+	+
Investment casting	+	+	+	—	+	+	+	+	+
Lost foam casting	—	—	—	+	+	+	+	—	—
Centrifugal casting	—	—	—	+	+	+	+	—	+
Tilt pouring	—	—	—	+	+	+	+	—	+
Squeeze casting	—	+	—	+	—	—	+	—	—

Finite Difference Method (FDM), used in programs such as Magmasoft, SolidCast, CastCAE, JSCAST, AnyCasting and others, allows you to quickly obtain the stress pattern of shrinkage defects in the designed casting and correct the casting technology in time. It is based on differential equations, in which the differential operators are replaced by finite-difference relations of varying degrees of accuracy. As a rule, they are built on orthogonal meshes, which makes it possible to factorize operators and reduce the solution of a multidimensional problem to a sequence of one-dimensional problems, which means much simplify and speed up the solution of the general system of equations. The disadvantages include the poor boundary approximation of complex areas, which is not too fundamental for the heat-conduction equations, but rather essential for the hydrodynamic equations.

Table 7 – Numerical methods in selected casting simulation software

Solution method	Auto Cast	CAP Cast	Cast CAE	Flow 3D Cast	Magma Soft	Nova-Solid/ Flow	Pro Cast	Solid Cast	Poly-gon
Finite Element Method	—	—	—	—	—	—	+	—	+
Finite Difference Method	—	—	—	+	+	—	—	+	—
Finite Volume Method	—	—	+	+	—	—	—	—	—
Vector Finite Element Method	+	—	—	—	—	—	—	—	—

To eliminate internal shrinkage in critical castings, such a method is not suitable, since the applied mathematical tool does not work well enough in the case of rangy castings when the wall thickness becomes comparable to the mesh spacing. This is because the splitting of the original geometric model occurs by imposing a rectangular mesh with a constant step, which leads to a sharp increase in the number of computational cells in the case of obtaining rangy castings of large overall dimensions.

The Finite Element Method (FEM) used in programs such as Polygon, WinCast, CAPCast, and others, allows maximum consideration of the casting geometry and reveals even minor defects. It is based on heat and mass transfer integral equations [6]. The solution region in which the equations are solved is divided into finite elements (most often - tetrahedrons), within which approximants of functions are constructed based on the system of basis functions defined on the element. By projecting the integral equations onto these bases, we obtain a system of finite-difference equations. This system is much more complicated than the one adopted in FDM; its solution requires large memory resources and considerable time.

The advantage of FEM is a proper boundary approximation, the disadvantages include the need for a high-quality generator of finite elements; the complexity of equations, and impossibility of factorization.

The built-in generators of the mesh model give large errors in the programs. The problem is solved by using an external finite element mesh generator, which leads to an increase in the cost of purchased software, operating time, and also requires highly qualified personnel.

At first glance, FDM and FEM differ in the representation of geometry, in the FDM the geometry is represented by bricks (parallelepipeds), and the FEM uses a fairly smooth mesh of finite elements (tetrahedra) of arbitrary sizes and configuration. This difference is not always clearly visible, because the visualization does not necessarily show a distorted brick geometry on the computer screen. It is possible to visualize the different solution on smooth surface meshes of the original geometric models so that the bricks were not visible. However, it is not a question of the modeled casting configuration, but a significant difference in the basic postulates of these methods and, as a consequence, in the different reliability of the solution.

FEM has a fundamentally more complex and adequate mathematical apparatus and more accurately describes the processes occurring in the considered geometric model. When simulating foundry processes FDM and FEM can have significant differences in the adequacy of the solution. It should be noted that currently almost all universal modeling packages, such as ANSYS, Nastran, Patran, etc. have long ago waived the deprecated FDM and use only FEM. More advanced foundry packages, such as ProCast, WinCast, Polygon, have followed the same path. The fact is that FDM is not suitable for complex geometries in problems with a significant influence of boundary flows. For casting conditions, this means that finite-difference methods can be adequately used for casting in disposable molds with low thermal conductivity when there is no jump in the simulated function (eg temperature) at the casting mold boundary.

For pressure die casting, especially for complex shaped geometries, FDM will always give a fundamental systematic inaccuracy that is absent in FEM. In addition, FEM is a less resource-intensive and faster method. For the same geometries, both methods give the same solution, but the FEM, when requiring equal adequacy with FDM, always requires about an order of magnitude less computational resources and the calculation time will be several times less. The use of FDM in the foundry processes simulation is now justified only for solving hydrodynamic problems during pouring, since the magnitudes and directions of the velocity vectors change with greater discreteness than can be described by a finite-element mesh without losing the advantages of FEM in terms of calculation speed.

In software packages such as ProCast, Flow3D Cast, and Polygon, all major foundry problems are solved base on FEM, and especially for hydrodynamic problems, either FDM or intermediate methods are used. Often, the visualization of the conditional-difference solution in such basic-element packages is performed on a finite-element mesh, which is faster and more convenient.

The disadvantage is that most FEM-based programs have a very complex user interface, which in combination with the lack of experience with software products of foundry technologists reduces the benefits of using any simulation program to zero.

The Finite Volume Method (FVM) used in Nova-Solid/Flow and CastCAE programs is an integrated circuit. In a sense, it is a development of FDM, although sometimes it is considered as some intermediate stage between FDM and FEM. This is probably not entirely true, although FVM takes into account arbitrarily oriented boundaries within the difference cell, but assumes orthogonal difference subdivision (sampling) into rectangular parallelepipeds and has several other features inherent in FDM. FVM is a convenient method for using integral formulations when considering boundary conditions, it allows to control of mesh elements at the casting-mold boundary and simulate the processes of pouring and solidification of casting. FVM successfully solves filling problems, where the use of FEM is difficult, and FDM does not give the necessary conformity in the geometry of the filled cavity.

The software products Flow3DCast and LVMFlow also use FVM, which combines the simplicity and factorization of FDM, as well as a good approximation of the boundaries between different materials and phases It allows simulations to be carried out as quickly as possible without losing the accuracy of the calculations and provides reliable results even with coarse meshes. In any case, FVM has not yet become widespread for modeling casting processes, this is probably due precisely to the intermediate nature of the method. In those cases when arbitrarily oriented boundaries are required, it is better to use FEM itself, and when it is permissible to represent the geometry by a set of parallelepipeds, it is easier to solve the problem with classical FDM.

The Vector Element Method (VEM) used in the AutoCast program is based on determining the greatest thermal gradient at any point inside the casting, which is set by the vector sum of the flux vectors in all directions from this point. The volume of the casting is divided into numerous pyramidal sectors from the considered point. Heat content and the surface area or cooling are calculated for each sector to determine the flux vector. The calculation is carried out in the direction of the resulting vector until the resulting one becomes zero. The feed line path is considered the curve along which the repetitions are done. It is possible to identify different hot spots in casting if the calculation starts with a plurality of starting points located in different areas of the casting.

VEM is relatively simple when compared to other numerical techniques but provides reliable and robust results. Unlike FEM or FDM methods, VEM rectifies small errors while computing flux vectors at any point by automatically correcting them in subsequent repetitions. Moreover, VEM requires less memory and is also faster.

The boundary element method (BEM) is the most "strong" method since in its basic formulation it assumes within the boundary element the approximation of the distribution of the desired excosecant (for example, the temperature excosecant) directly according to the original differential equation, which describes the simulated process. In addition, when using BEM, spatial ordering occurs, which theoretically speeds up the solution and reduces the requirements for computing resources. However, for modeling casting processes, BEM is practically not used, because, despite of its advantages, it requires uniformity of physical properties in the areas of large boundary elements. This does not correspond to the physics of most casting processes associated with a significant change in the process parameters in local arbitrary areas, for example, in the area of heat output during solidification.

Practice shows that the optimal approach is not to choose a single numerical method to simulate casting processes but to use a combination of different methods, which makes it possible to increase the speed, accuracy, and adequacy of the results obtained to experimental data.

MagmaSoft – is a multifunctional specialized program that allows you to simulate a variety of casting processes. This is one of the first commercial foundry packages, actually demonstrating for the first time that complex casting processes can be broadly simulated at a sufficiently high level. Thermal, hydrodynamic, and deformation processes are solved by numerical methods in MagmaSoft. The problem of predicting macroporosity and cavities is also numerically solved, although the models used in this case are simplified and do not fully take into account the complex and dynamic nature of the structuring of alloys during solidification. Forecast of microporosity, structural, mechanical, and other characteristics of casting is carried out at the level of criterion analysis.

The advantage of MagmaSoft is the presence of a sufficiently large number of empirical criteria, which at the level of criteria analysis allow predicting various properties, including the structure and mechanical characteristics of castings. In addition, the program implicitly integrates into the system various superimposed coefficients for a variety of casting methods, alloys, and materials, which to some extent compensates for the simplification of models and algorithms.

MagmaSoft has a convenient generator of difference meshes. If the initial geometry of the castings is relatively simple or the task of exact adherence the ratios of different wall thicknesses and a sufficient number of finite-difference elements along the wall thickness is not posed, then the generation of the calculated difference geometric model does not present any particular difficulties.

The disadvantage of this system is that the criteria used are hidden and it is impossible to edit, customize and supplement them, which significantly reduces the possibility of their adequate application. The above is also true of the choice of initial conditions, which are closed to the user and are determined by the casting method. This approach is acceptable for typical, widely used technologies. However, the lack of information on the choice of production parameters laid down in the system leads to the fact that the calculation results are often conditional.

In general, MagmaSoft is a system focused on solving typical casting tasks, except for special casting methods and technologies for producing castings of complex geometry. The program has good accuracy of the results obtained and a rich set of parameters for the simulation. MagmaSoft's long experience with foundries around the world has earned it a reputation for being a simple, reliable, and accurate package.

ProCast computer system, unlike MagmaSoft, is an extensive set of complex and physically universal models for solving serious production problems in the foundry industry, which significantly increases the adequacy of calculations. This system simulates thermal, hydrodynamic, and deformation processes, as well as processes of structurization and crystallization. The program is able to forecast the occurrence of deformations and residual stresses in the casting and can be used to analyze such processes as core making, centrifugal casting, cavityless casting, and continuous casting. An accurate description of the geometry, due to the applied FEM, allows the ProCast system to simulate the filling of a mold with supernatant liquid and obtain reliable information about the erosion of a sand mold, air pockets, oxides, and turbulent flow, material age, nonspillages, and cold junctions, flow length and, overflows over-pours.

ProCast provides a complete solution for the simulation of the continuous and semi-continuous casting of billets. The program can simulate the steady-state mode, the initial and final stages of the process. The inverse calculation module automatically calculates the parameters of a material or process based on temperatures measured at targeted points or at the predetermined times. Primary and secondary cooling can be determined by inverse calculation. This computer system has its own finite element mesh generator, which can be successfully used for geometries of medium complexity. For complex geometry models, specialized external generators are commonly used, which are currently available on the market.

A large database of materials for foundry models comes with ProCast. Its content is constantly updated with reliable data, verified in the conditions of existing foundry production. It includes the unique thermodynamic database that allows the user (by entering the chemical composition of the alloy) to automatically obtain the temperature curves of the properties necessary for an accurate calculation of the casting process.

The main advantages of this package include the ability to take into account complex thermal boundary conditions and direction of solidification, complex rheology in deformation calculations, the ability to simulate complex processes and numerically calculate the structure in castings. To carry out numerical calculations of the structure in ProCast, it is necessary to select the correct crystallization model and its parameters.

The disadvantage of the program is a too low level of solving the shrinkage problem, as well as the high cost, but it is justified by the capabilities of the program.

Thus, ProCast can be recommended as a basic system for castings and technologies of any complexity, excluding those cases where it is required to simulate the formation of shrinkage defects, taking into account the real dynamic nature of the structuring of the two-phase zone and the pressure drop due to filtration flow in the two-phase zone during shrinkage. This package is effective when technologists need to solve deformation problems with complex rheology and structure in the casting.

WinCast is a software package for casting processes simulation capable of calculating metal pouring (hydrodynamic and thermal analysis), metal crystallization (location of heat units and shrinkage defects),the tension of a casting (forecasts technological and operational stresses), structure-forming processes, heat treatment, and welding. The basis of the modular system is made up of basic and additional modules for sequential or parallel passage of various stages of modeling, and the solution of problems can be carried out jointly, taking into account their cross-impact.

Compared to Procast, WinCast has a more convenient process for building a mesh models, not inferior in the accuracy of calculations. The advantages of this model are the following: more accurate approximation of complex surfaces; more accurate representation of thin walls and complex sections with fewer elements; the ability to carry out thermal, hydrodynamic, and strength analysis on one mesh; fewer heat units reduce the calculation time.

The accuracy of thermal calculations is ensured by the correct approximation of surfaces by finite elements and by taking into account the temperature dependence of the properties of alloys and auxiliary materials. The reliability of hydrodynamic and strength analyzes is guaranteed by the compatible calculation of temperature fields on the same finite element pentahedral mesh with a high level of regularity. Generation of an accurate finite element mesh for 3D geometry of any complexity, built in an external CAD system or using the program's tools, provides accurate engineering forecasts in a short time.

The advantage of WinCast is that the database, organized in text format, is easy to edit and supplement. It contains the properties of alloys and materials in the form of tabular function of temperature. Thanks to a flexible preprocessor, the program provides accurate geometry display and the availability of automatic mesh generation.

Among the disadvantages, it should be noted is an inconvenient interface, as well as the use of simplified models when solving the heat problem (solidification) and the shrinkage-filtration problem (the formation of micro-and macroporosity). The inability to automatically generate the computational grid requires additional spadework to create it. However, in WinCast, deformation processes are simulated at a sufficiently high level as a result of casting cooling.

SolidCast is an entry-level computer system that is designed to solve current production and technological problems, as well as to optimize the technology for each casting based on the geometry optimization of the gating-feeding system and the technological parameters of the casting process.

The computational capabilities of the package allow the user to trace the dynamics of filling the mold with metal and the crystallization process of the casting in the mold; to obtain information about the time of crystallization, the rate of cooling, shrinkage defects; to determine the possible areas of defect occurrences in the casting. The built-in hydrodynamic module allows you to simulate the flow of the melt in the mold, as a result of which it is possible to identify and forecast such defects as mold erosion, cast seams, surface contaminations, and misruns in the casting. As a result of the calculation, the technologist receives information about the allocation of temperature fields in the casting and the mold, the values of the melt flow rate, and the pressure of the melt on the mold walls at any point.

SolidCast has a built-in mesh generator in two versions and an automatic generator of graphs and diagrams in the postprocessor, which allows comparing the simulation results of several variants of manufacturing technologies for the same casting. The availability in the SolidCast computer system of the possibility of automatic generation of the computational mesh permits optimizing the casting mold depending on scrap yield and the size of the flask. In addition, this software product allows to creation of a unique database on the used technological processes for casting production. The built-in database of molding materials and alloys is open to the user, it is constantly changing and supplemented.

The disadvantages of SolidCast are as follows: inconvenient interface, inability to take into account preliminary mold filling; inconvenient display of calculation results for visual analysis; excessive duration of computer calculations. Extensive functionality and unique pricing policy of developers make SolidCast the best in terms of price-functionalities-productivity since one acquired licensed program can be used at five workplaces within one enterprise.

The **Polygon** computer system is designed to simulate hydrodynamic, thermal, and shrinkage-filtration processes during casting. In addition, the problem of reticulation of electric potentials during solidification of casting in the electric fields is solved by numerical methods. Criteria analysis methods allow predicting strength, hardness, structural parameters, and erosion of forms.

When using the Polygon software, simulation is carried out based on the finite element method, which allows using the most adequate physical and geometric models. All models and functions are implemented for 3D geometric models. Solvers can use not only direct but also iterative calculation methods. This makes it possible to significantly reduce the calculation time and the required random access memory, which in combination with the finite element method, calculaties castings of any complexity available on a personal computer.

Based on the criterion analysis, the Polygon system package contains a special module that allows using not only the criteria proposed by the developers for predicting mechanical properties, but also to form a base of own complex criteria, taking into account the chemical composition and the logic of transition from one formula to another. This enables the user to adequately forecast various technological and operational properties of the casting.

The possibility of taking into account complex boundary conditions for castings of complex geometry when using special casting methods makes it possible to use the Polygon computer program in complex foundries, in particular, by methods of directional solidification. One of the most important properties of Polygon is adequate and modern physical models of the shrinking process. It carries out a combined calculation of the formation of shrinkage micro and macro defects by two completely different mechanisms with the calculation of the filtration flow, pressure fields in the casting, and complex dynamic changes in the structuredness of the alloy in the solidification interval. The problem of shrinking the defects in numerical solutions in other casting packages is not solved.

When choosing the properties of alloys, materials, boundary, and other conditions, the user has full access to all parameters, also can change and supplement the initial databases by properties in any way.

The disadvantages of the package include the absence of a full-scale deformation task taking into account complex rheology and the excessive complexity of models when solving hydrodynamic problems, namely: an extremely inconvenient interface; the complexity of preparing mesh model, the complexity of data entry, an insufficient database of materials and alloys, as well as the need for purchasing additional software for generating the mesh model.

Thus, Polygon is a modeling system designed to solve the problems of casting technology simulation for any casting method with unlimited complexity of the casting geometry, taking into account the maximum number of operating factors. The advantages of the package, in addition to the use of finite elements, include complex and adequate physical models of thermal processes, the ability to take into account complex boundary conditions, and displacement of objects (for directional casting solidification, as well as a comprehensive problem solving of shrinking. Practice shows that for essential castings, the Polygon program can be used in combination with other packages for foundry processes simulation as testing tools for developing the optimal technology for producing castings.

GLOSSARY

A

acid - a term applied to slags, refractories and minerals containing a high percentage of silica;

acidity - the degree to which a material is acid, furnace refractories are ranked by their acidity;

acid process - a steelmaking method using an acid refractory-lined furnace; neither sulfur nor phosphorus is removed;

acid refractory - siliceous ceramic materials of a high melting temperature, such as silica brick, used for metallurgical furnace linings; compare with basic refractory;

addition agent - (1) any material added to a charge of molten metal in a bath or ladle to bring the alloy to specifications; (2) reagent added to plating bath;

additive - any material added to molding sand for reasons other than bonding, for example, seacoal, pitch, graphite, cereals;

aerate - to fluff up molding sand to reduce its density;

airblasting - see blasting or blast cleaning;

air channel - a groove or hole that carries the vent from a core to the outside of a mold;

air dried - refers to the air drying of a core or mold without the application of heat;

air-dried strength - strength (compressive, shear or tensile) of a refractory (sand) mixture after being air dried at room temperature;

air furnace - reverberatory-type furnace in which metal is melted by heat from fuel burning at one end of the hearth, passing over the bath toward the stack at the other end; heat is also reflected from the roof and sidewalls;

air hole - a hole in a casting caused by air or gas trapped in the metal during solidification;

air setting - the characteristic of some materials, such as refractory cements, core pastes, binders and plastics, to take permanent set at normal air temperature**s;**

allowance - in a foundry, the specified clearance; the difference in limiting sizes, such as minimum clearance or maximum interference between mating parts, as computed arithmetically;

alpha process - a shell molding and coremaking method in which a thin resinbonded shell is baked with a less expensive, highly permeable material;

alumina - the mineral aluminum oxide (Al_2O_3) with a high melting point (refractory) that is sometimes used as a molding sand;

angularity - the angular relationship of one surface to another; specifically, the dimensional tolerance associated with such features on a casting;

arbitration bar - a test bar, cast with a heat of material, used to determine chemical composition, hardness, tensile strength and deflection and strength under transverse loading in order to establish the state of acceptability of the casting;

arbor - a metal shape embedded in and used to support green or dry sand cores in the mold;

arc furnace - a furnace in which metal is melted either directly by an electric arc between an electrode and the work or indirectly by an arc between two electrodes adjacent to the metal;

arc melting - melting metal in an electric arc furnace;

as-cast condition - castings as removed from the mold without subsequent heat treatment;

atmospheric riser - a riser that uses atmospheric pressure to aid feeding; essentially, a blind riser into which a small core or rod protrudes; the function of the core or rod is to provide an open passage so that the molten interior of the riser will not be under a partial vacuum when metal is withdrawn to feed the casting but will always be under atmospheric pressure;

austenite - a solid solution of one or more elements in face-centered cubic iron (gamma iron); unless otherwise designated (such as nickel austenite), the solute is generally assumed to be carbon.

B

back draft - a reverse taper that prevents removal of a pattern from a mold or a core from a core box;

backing board (backing plate) - a second bottom board on which molds are opened;

backup coat - the ceramic slurry of dip coat that is applied in multiple layers to provide a ceramic shell of the desired thickness and strength for use as a mold;

bake - heating in an oven to a low controlled temperature to remove gases or to harden a binder;

baked core - a core that has been heated through sufficient time and temperature to produce the desired physical properties attainable from its oxidizing or thermal-setting binders;

bank sand - sedimentary deposits, usually containing less than 5% clay, occurring in banks or pits, used in coremaking and in synthetic molding sands;

basic refractory - a lime- or magnesia-base ceramic material of high melting temperature used for furnace linings;

batch - an amount of core or mold sand or other material prepared at one time;

bath - molten metal on the hearth of a furnace, in a crucible or in a ladle;

bead - (1) half-round cavity in a mold or half-round projection or molding on a casting; (2) a single deposit of weld metal produced by fusion;

bedding - sinking a pattern down into the sand to the desired position and ramming the sand around it;

bedding a core - placing an irregularly shaped core on a bed of sand for drying;

bench molding - making sand molds by hand tamping loose or production patterns at a bench without the assistance of air or hydraulic action;

bentonite - a colloidal claylike substance derived from the decomposition of volcanic ash composed chiefly of the minerals of the montmorillonite family; it is used for bonding molding sand;

bimetal - a casting made of two different metals, usually produced by centrifugal casting;

binder - a material used to hold the grains of sand together in molds or cores; it may be cereal, oil, clay or natural or organic resins;

blacking - carbonaceous materials, such as graphite or powdered carbon, usually mixed with a binder and frequently carried in suspension in water or other liquid used as a thin facing applied to surfaces of molds or cores to improve casting finish;

blasting or blast cleaning - a process for cleaning or finishing metal objects with an air blast or centrifugal wheel that throws abrasive particles against the surface of the workpiece; small, irregular particles of metal are used as the abrasive in gritblasting; sand, in sandblasting; and steel balls, in shotblasting;

bleed - refers to molten metal oozing out of a casting; it is stripped or removed from the mold before complete solidification;

blended sand - a mixture of sands of different grain size and clay content that provides suitable characteristics for foundry use;

blind riser - a riser that does not extend through the top of the mold;

blister - a defect in metal, on or near the surface, resulting from the expansion of gas in a subsurface zone; it is characterized by a smooth bump on the surface of the casting and a hole inside the casting directly below the bump;

blow - a term that describes the trapping of gas in castings, causing voids in the metal;

blowhole - a void or large pore that may occur because of entrapped air, gas or shrinkage; usually evident in heavy sections;

blow holes - holes in the head plate or blow plate of a core blowing machine through which sand is blown from the reservoir into the core box;

bond clay - any clay suitable for use as a bonding agent in molding sand;

bond strength - the degree of cohesiveness that the bonding agent exhibits in holding sand grains together;

bonding agent - any material other than water that, when added to foundry sands, imparts strength either in the green, dry or fired state;

boss - a relatively short protrusion or projection from the surface of a forging or casting, often cylindrical in shape; usually intended for drilling and tapping for attaching parts;

bottom board - a flat base for holding the flask in making sand molds;

bottom-pour ladle - a ladle from which metal, usually steel, flows through a nozzle located at the bottom;

bottom running or pouring - filling of the mold cavity from the bottom by means of gates from the runner;

bridging - (1) premature solidification of metal across a mold section before the metal below or beyond solidifies; (2) solidification of slag within a cupola at or just above the tuyeres;

buckle - (1) bulging of a large, flat face of a casting; in investment casting, caused by dip coat peeling from the pattern; (2) an indentation in a casting, resulting from expansion of the sand, can be termed the start of an expansion defect;

bumper - a machine used for packing molding sand in a flask by repeated jarring or jolting;

burned-in sand - a defect consisting of a mixture of sand and metal cohering to the surface of a casting;

burned-on sand - a misnomer usually indicating metal penetration into sand resulting in a mixture of sand and metal adhering to the surface of a casting;

burnout - firing a mold at a high temperature to remove pattern material residue;

burned sand - sand in which the binder or bond has been removed or impaired by contact with molten metal.

C

calcium silicon - an alloy of calcium, silicon and iron containing 28 to 35% Ca, 60 to 65% Si and 6% Fe (max), used as a deoxidizer and degasser for steel and cast iron; sometimes called calcium silicide;

carbonaceous - a material that contains carbon in any or all of its several allotropic forms;

carbon dioxide process (sodium silicate/CO_2) - a process for hardening molds or cores in which carbon dioxide gas is blown through dry clay- free silica sand to precipitate silica in the form of a gel from the sodium silicate binder;

carbon refractory - a manufactured refractory comprised substantially or entirely of carbon (including graphite);

castability - (1) a complex combination of liquid-metal properties and solidification characteristics that promotes accurate and sound final castings; (2) the relative ease with which a molten metal flows through a mold or casting die;

castable - a combination of refractory grain and suitable bonding agent that, after the addition of a proper liquid, is generally poured into place to form a refractory shape or structure that becomes rigid because of chemical action;

casting - (1) metal object cast to the required shape by pouring or injecting liquid metal into a mold, as distinct from one shaped by a mechanical process; (2) pouring molten metal into a mold to produce an object of desired shape;

casting defect - any imperfection in a casting that does not satisfy one or more of the required design or quality specifications; this term is often used in a limited sense for those flaws formed by improper casting solidification;

casting section thickness - the wall thickness of the casting; because the casting may not have a uniform thickness, the section thickness may be specified at a specific place on the casting; also, it is sometimes useful to use the average, minimum or typical wall thickness to describe a casting;

casting shrinkage - the amount of dimensional change per unit length of the casting as it solidifies in the mold or die and cools to room temperature after removal from the mold or die. There are three distinct types of casting shrinkage; liquid shrinkage refers to the reduction in volume of liquid metal as it cools to the liquidus; solidification shrinkage is the reduction in volume of metal from the beginning to the end of solidification; solid shrinkage involves the reduction in volume of metal from the solidus to room temperature;

casting stresses - stresses set up in a casting because of geometry and casting shrinkage;

casting thickness - see casting section thickness;

casting volume - the total cubic units (mm^3 or in^3) of cast metal in the casting;

casting yield - the weight of a casting(s) divided by the total weight of metal poured into the mold, expressed as a percentage;

cast iron - a generic term for a large family of cast ferrous alloys in which the carbon content exceeds the solubility of carbon in austenite at the eutectic temperature; most cast irons contain at least 2% C, plus silicon and sulfur and may or may not contain other alloying elements, for the various forms, the word cast is often left out, resulting in compacted graphite iron, gray iron, white iron, malleable iron and ductile iron;

cast structure - the internal physical structure of a casting evidenced by the shape and orientation of crystals and the segregation of impurities;

cavity - the mold or die impression that gives a casting its external shape;

cementite - a very hard and brittle compound of iron and carbon corresponding to the empirical formula Fe_3C, commonly known as iron carbide;

centerline shrinkage - shrinkage or porosity occurring along the central plane or axis of a cast part;

centrifugal casting - the process of filling molds by (1) pouring metal into a sand or permanent mold that is revolving about either its horizontal or its vertical axis or (2) pouring metal into a mold that is subsequently revolved before solidification of the metal is complete;

centrifuge casting - a casting technique in which mold cavities are spaced symmetrically about a vertical axial common downgate; the entire assembly is rotated about that axis during pouring and solidification;

ceramic - material of a nonmetallic nature, usually refractory, made from fused, sintered or cemented metallic oxides;

ceramic molding - a precision casting process that employs permanent patterns and fine-grain slurry for making molds; unlike monolithic investment molds, which are similar in composition, ceramic molds consist of a cope and a drag or, if the casting shape permits, a drag only;

CG iron - same as compacted graphite iron;

chaplet - metal support that holds a core in place within a mold; molten metal solidifies around a chaplet and fuses it into the finished casting;

charge - (1) the materials placed in a melting furnace; (2) castings placed in a heat-treating furnace;

check - a minute crack in the surface of a casting caused by unequal expansion or contraction during cooling;

chill - (1) a metal or graphite insert embedded in the surface of a sand mold or core or placed in a mold cavity to increase the cooling rate at that point; (2) white iron occurring on a gray or ductile iron casting, such as the chill in the wedge test;

chill coating - applying a coating to a chill that forms part of the mold cavity so that the metal does not adhere - to it or applying a special coating to the sand surface of the mold that causes the iron to undercool;

chilled iron - cast iron that is poured into a metal mold or against a mold insert so as to cause the rapid solidification that often tends to produce a white iron structure in the casting;

clay - a natural, earthy, fine-grain material that develops plasticity when mixed with a limited amount of water; foundry clays, which consist essentially of hydrous silicates of alumina, are used in molds and cores;

CO_2 process - see carbon dioxide process;

coining - (1) the process of straightening and sizing castings by die pressing; (2) a press metalworking operation that establishes accurate dimensions of flat surfaces or depressions under predominantly compressive loading;

coke - a porous, gray, infusible product resulting from the dry distillation of bituminous coal, petroleum or coal tar pitch that drives off most of the volatile matter;

coke bed - the first layer of coke placed in the cupola; also the coke used as the foundation in constructing a large mold in a flask or pit;

coke breeze - fines from coke screenings, used in blacking mixes after grinding; also briquetted for cupola use;

coke furnace - type of pot or crucible furnace that uses coke as the fuel;

cold box process - a two-part organic resin binder system mixed in conventional mixers and blown into shell or solid core shapes at room temperature; a vapor mixed with air is blown into the core, permitting instant setting and immediate pouring of metal around it;

cold chamber machine - a die casting machine with an injection system that is charged with liquid metal from a separate furnace;

cold cracking - cracks in cold or nearly cold metal due to excessive internal stress caused by contraction; often brought about when the mold is too hard or the casting is of unsuitable design;

cold lap - wrinkled markings on the surface of an ingot or casting from incipient freezing of the surface and too low a casting temperature;

cold-setting process - any of several systems for bonding mold or core aggregates by means of organic binders, relying on the use of catalysts rather than heat for polymerization (setting);

cold shot - (1) a portion of the surface of an ingot or casting showing premature solidification; caused by splashing of molten metal onto a cold mold wall during pouring; (2) small globule of metal embedded in, but not entirely fused with, the casting;

cold shut - (1) a discontinuity that appears on the surface of cast metal as a result of two streams of liquid meeting and failing to unite; (2) a lap on the surface of a forging or billet that was closed without fusion during deformation; (3) freezing of the top surface of an ingot before the mold is full;

collapsibility - the tendency of a sand mixture to break down under the pressures and temperatures developed during casting;

columnar structure - a coarse structure of parallel columns of grains, that is caused by highly directional solidification resulting from sharp thermal gradients;

combination die (multiple-cavity die) - in die casting, a die with two or more different cavities for different castings;

combined carbon - carbon in iron that is combined chemically with other elements; not in the free state as graphite or temper carbon; the difference between the total carbon and the graphite carbon analyses;

compacted graphite iron - cast iron having a graphite shape intermediate between the flake form typical of gray iron and the spherical form of fully spherulitic ductile iron, also known as CG iron or vermicular iron, compacted graphite iron is produced in a manner similar to that for ductile iron but with a technique that inhibits the formation of fully spherulitic graphite nodules;

constraint - any restriction that limits the transverse contraction normally associated with a longitudinal tension and therefore causes a secondary tension in the transverse direction;

consumable-electrode remelting - a process for refining metals in which an electric current passes between an electrode made of the metal to be refined and an ingot of the refined metal, which is contained in a water-cooled mold. As a result of the passage of electric current, droplets of molten metal form on the electrode and fall to the ingot. The refining action occurs from contact with the atmosphere, vacuum or slag through which the drop falls;

continuous casting - a process for forming a bar of constant cross section directly from molten metal by gradually withdrawing the bar from a die as the metal flowing into the die solidifies;

contraction - the volume change that occurs in metals and alloys upon solidification and cooling to room temperature;

convection - the motion resulting in a fluid from the differences in density and the action of gravity. In heat transmission, this meaning has been extended to include both forced and natural motion or circulation;

cooling stresses - stresses developed during cooling by the uneven contraction of metal, generally due to nonuniform cooling;

cope - the upper or topmost section of a flask , mold or pattern;

core - (1) a specially formed material inserted in a mold to shape the interior or other part of a casting that cannot be shaped as easily by the pattern; (2) in a ferrous alloy prepared for case hardening, that portion of the alloy that is not part of the case. Typically considered to be the portion that (a) appears light on an etched cross section; (b) has an essentially unaltered chemical composition or (c) has a hardness, after hardening, less than a specified value;

core assembly - a complex core consisting of a number of sections;

core binder - any material used to hold the grains of core sand together;

core blow - a gas pocket in a casting adjacent to a cored cavity and caused by entrapped gases from the core;

core blower - a machine for making foundry cores using compressed air to blow and pack the sand into the core box;

core box - a wood, metal or plastic structure containing a shaped cavity into which sand is packed to make a core;

core dryers - supports used to hold cores in shape during baking; constructed from metal or sand for conventional baking or from plastic material for use with dielectric core-baking equipment;

core filler - material, such as coke, cinder and sawdust, used in place of sand in the interiors of large cores; usually added to aid collapsibility;

coring - a variable composition between the center and the surface of a unit of structure (such as a dendrite, grain or carbide particle) resulting from the none quilibrium growth that occurs over a range of temperature;

core knockout machine - a mechanical device for removing cores from castings;

coreless induction furnace - an electric induction furnace for melting or holding molten die casting metals that does not utilize a steel core to direct the magnetic field;

core oil - a binder for core sand that sets when baked and is destroyed by the heat from the cooling casting;

core plates - heat-resistant plates used to support cores during baking; may be metallic or nonmetallic, the latter being a requisite for dielectric core baking;

core print - projections attached to a pattern in order to form recesses in the mold at points where cores are to be supported;

core sand - sand for making cores to which a binding material has been added to obtain good cohesion and permeability after drying; usually low in clays;

core shift - a variation from the specified dimensions of a cored casting section due to a change in position of the core or misalignment of cores in assembly;

core vents - (1) a wax product, round or oval in form, used to form the vent passage in a core; also, a metal screen or slotted piece used to form the vent passage in the core box used in a core blowing machine; (2) holes made in the core for the escape of gas;

core wash - a suspension of a fine refractory applied to cores by brushing, dipping or spraying to improve the surface of the cored portion of the casting;

core wires or rods - reinforcing wires or rods for fragile cores, often preformed into special shapes;

corundum - native alumina or aluminum oxide, Al_2O_3, occurring as rhombohedral crystals and also in masses and variously colored grains; It is the hardest mineral except for the diamond; corundum and its artificial counterparts are abrasives especially suited to the grinding of metals;

coupon - a piece of metal from which a test specimen is to be prepared; often an extra piece (as on a casting or forging) or a separate piece made for test purposes (such as a test weldment);

cover core - (1) a core set in place during the ramming of a mold to cover and complete a cavity partly formed by the withdrawal of a loose part of the pattern; also used to form part or all of the cope surface of the mold cavity; (2) a core placed over another core to create a flat parting line;

critical dimension - a dimension on a part that must be held within the specified tolerance for the part to function in its application; A noncritical tolerance may be for cost or weight savings or for manufacturing convenience, but is not essential for the products;

croning process - a shell molding process that uses a phenolic resin binder; Sometimes referred to as C process or chronizing;

cross-sectional area - the area measured at right angles to the molten metal flow stream at any specified portion of the gating system;

crucible - a vessel or pot, made of a refractory substance or of a metal with a high melting point, used for melting metals or other substances;

crucible furnace - a melting or holding furnace in which the molten metal is contained in a pot-shaped (hemispherical) shell; electric heaters or fuel-fired burners outside the shell generate the heat that passes through the shell (crucible) to the molten metal;

crush - (1) buckling or breaking of a section of a casting mold due to incorrect register when the mold is closed; (2) an indentation in the surface of a casting due to displacement of sand when the mold was closed;

crush strip or bead - an indentation in the parting line of a pattern plate that ensures that cope and drag will have good contact by producing a ridge of sand that crushes against the other surface of the mold or core;

cupola - a cylindrical vertical furnace for melting metal, especially cast iron, by having the charge come in contact with the hot fuel, usually metallurgical coke;

curing time (no bake) - the period of time needed before a sand mass reaches maximum hardness;

cut - (1) to recondition molding sand by mixing on the floor with a shovel or blade-type machine; (2) to form the sprue cavity in a mold; (3) defect in a casting resulting from erosion of the sand by metal flowing over the mold or cored surface;

cut off - removing a casting from the sprue by refractory wheel or saw, arc-air torch or gas torch.

D

daubing - filling of cracks in molds or cores by specially prepared pastes or coatings to prevent penetration of metal into these cracks during pouring;

dead-burned - term applied to materials that have been fired to a temperature sufficiently high to render them relatively resistant to moisture and contraction;

defect - a discontinuity whose size, shape, orientation or location makes it detrimental to the useful service of the part in which it occurs;

defective - a quality control term describing a unit of product or service containing at least one defect or having several lesser imperfections that, in combination, cause the unit not to fulfill its anticipated function;

degasification - see degassing;

degasifier - a substance that can be added to molten metal to remove soluble gases that might otherwise be occluded or entrapped in the metal during solidification;

degassing - (1) a chemical reaction resulting from a compound added to molten metal to remove gases from the metal; inert gases are often used in this operation; (2) a fluxing procedure used for aluminum alloys in which nitrogen, chlorine, chlorine, nitrogen, chlorine and argon are bubbled up through the metal to remove dissolved hydrogen gases and oxides from the alloy;

dendrite - a crystal that has a treelike branching pattern, being most evident in cast metals slowly cooled through the solidification range;

deoxidation - removal of excess oxygen from the molten metal; usually accomplished by adding materials with a high affinity for oxygen;

deoxidizer - a substance that can be added to molten metal to remove either free or combined oxygen;

deoxidizing - (1) the removal of oxygen from molten metals through the use of a suitable deoxidizer ; (2) sometimes refers to the removal of undesirable elements other than oxygen through the introduction of elements or compounds that readily react with them; (3) in metal finishing, the removal of oxide films from metal surfaces by chemical or electrochemical reaction;

dephosphorization - the elimination of phosphorus from molten steel;

descaling - a chemical or mechanical process for removing scale or investment material from castings;

desulfurizing - the removal of sulfur from molten metal by reaction with a suitable slag or by the addition of suitable compounds;

dewaxing - the process of removing the expendable wax pattern from an investment mold or shell mold; usually accomplished by melting out the application of heat or dissolving the wax with an appropriate solvent;

die casting - (1) a casting made in a die; (2) a casting process in which molten metal is forced under high pressure into the cavity of a metal mold;

die pull - the direction in which the solidified casting must move when it is removed from the die; the die pull direction must be selected such that all points on the surface of the casting move away from the die cavity surfaces;

die separation - the space between the two halves of a die casting die at the parting surface when the dies are closed. The separation may be the result of the internal cavity pressure exceeding the locking force of the machine or warpage of the die due to thermal gradients in the die steel;

dip coat - (1) in the solid mold technique of investment casting, an extremely fine ceramic precoat applied as a slurry directly to the surface of the pattern to reproduce maximum surface smoothness. This coating is surrounded by coarser, less expensive and more permeable investment to form the mold; (2) in the shell mold technique of investment casting, an extremely fine ceramic coating called the first coat, applied as a slurry directly to the surface of the pattern to reproduce maximum surface smoothness. The first coat is followed by other dip coats of different viscosity and usually containing different grading of ceramic particles; after each dip, coarser stucco material is applied to the still-wet coating;

directional solidification - solidification of molten metal in such a manner that feed metal is always available for that portion that is just solidifying;

discontinuity - any interruption in the normal physical structure or configuration of a part, such as cracks, laps, seams, inclusions or porosity; a discontinuity may or may not affect the utility of the part;

distortion - any deviation from the desired shape or contour;

dolomite brick - a calcium magnesium carbonate ($CaMg(CO_3)_2$) used as a refractory brick that is manufactured substantially or entirely of dead-burned dolomite;

dowel - (1) a wooden or metal pin of various types used in the parting surface of parted patterns and core boxes; (2) in die casting dies, metal pins to ensure correct registry of cover and ejector halves;

downgate - same as sprue;

draft - (1) an angle or taper on the surface of a pattern, core box, punch or die (or of the parts made with them) that facilitates removal of the parts from a mold or die cavity or a core from a casting; (2) the change in cross section that occurs during rolling or cold drawing;

drag - the bottom section of a flask, mold or pattern;

draw - a term used to denote the shrinkage that appears on the surface of a casting; formerly used to describe tempering;

drawing (pattern) - removing a pattern from a mold or a mold from a pattern in production work;

draw plate - a plate attached to a pattern to facilitate drawing of a pattern from the mold;

drop - a casting imperfection due to a portion of the sand dropping from the cope or other overhanging section of the mold;

dross - the scum that forms on the surface of molten metal largely because of oxidation but sometimes because of the rising of impurities to the surface;

dry and baked compression test - an American Foundrymen's Society test for determining the maximum compressive stress that a baked sand mixture is capable of developing;

dry permeability - the property of a molded mass of sand, bonded or unbonded, dried at ~100 to 110 °C (~220 to 230 °F) and cooled to room temperature, that allows the transfer of gases resulting during the pouring of molten metal into a mold;

dry sand casting - the process in which the sand molds are dried at above 100 °C (212 °F) before use;

dry sand mold - a casting mold made of sand and then dried at ~100°C (~220°F) or above before being used;

dry strength - the maximum strength of a molded sand specimen that has been thoroughly dried at ~100 to 100°C (~220 to 230°F) and cooled to room temperature; also known as dry bond strength;

dual-metal centrifugal casting - centrifugal castings produced by pouring a different metal into the rotating mold after the first metal poured has solidified; also referred to as bimetal casting;

ductile iron - a cast iron that has been treated while molten with an element such as magnesium or cerium to induce the formation of free graphite as nodules or spherulites, which imparts a measurable degree of ductility to the cast metal; also known as nodular cast iron, spherulitic graphite cast iron and SG iron.

E

ejector - a pin (rod) or mechanism that pushes the solidified die casting out of the die;

ejector pin - see ejector;

electric arc furnace - see arc furnace;

electric furnace - a metal melting or holding furnace that produces heat from electricity; It may operate on the resistance or induction principle;

electrode - compressed graphite or carbon cylinder or rod used to conduct electric current in electric arc furnaces, arc lamps, carbon arc welding and so forth;

electroslag remelting - a consumable-electrode remelting process in which heat is generated by the passage of electric current through a conductive slag; the droplets of metal are refined by contact with the slag;

endothermic reaction - designating or pertaining to a reaction that involves the absorption of heat;

equiaxed grain structure - a structure in which the grains have approximately the same dimensions in all directions;

ethyl silicate - a strong bonding agent for sand and refractories used in preparing molds in the investment casting process;

eutectic - (1) an isothermal reversible reaction in which a liquid solution is converted into two or more intimately mixed solids upon cooling, the number of solids formed being the same as the number of components in the system, (2) an alloy having the composition indicated by the eutectic point on an equilibrium diagram; (3) an alloy structure of intermixed solid constituents formed by a eutectic reaction;

exothermic reaction - chemical reactions involving the liberation of heat, such as the burning of fuel or the deoxidizing of iron with aluminum;

expendable pattern - a pattern that is destroyed in making a casting; it is usually made of wax (investment casting) or expanded polystyrene (lost foam casting).

F

facing - any material applied in a wet or dry condition to the face of a mold or core to improve the surface of the casting;

feeder (feeder head, feedhead) - a riser;

feeding - (1) in casting, providing molten metal to a region undergoing solidification, usually at a rate sufficient to fill the mold cavity ahead of the solidification front and to compensate for any shrinkage accompanying solidification, (2) conveying metal stock or workpieces to a location for use or processing, such as wire to a consumable electrode, strip to a die or workpieces to an assembler;

ferrite - an essentially carbon-free solid solution in which alpha iron is the solvent and which is characterized by a body-centered cubic crystal structure;

ferroalloy - an alloy of iron that contains a sufficient amount of one or more other chemical elements to be useful as an agent for introducing these elements into molten metal, especially into steel or cast iron;

ferrous - metallic materials in which the principal component is iron;

fillet - concave corner piece usually used at the intersection of casting sections; also the radius of metal at such junctions as opposed to an abrupt angular junction;

fillet radius - blend radius between two abutting walls;

fin - metal on a casting caused by an imperfect joint in the mold or die;

finish allowance - amount of stock left on the surface of a casting for machining;

firebrick - a refractory brick, often made from fireclay , that is able to withstand high temperature (1500 to 1600 °C or 2700 to 2900 °F) and is used to line furnaces, ladles or other molten metal containment components;

fireclay - a mineral aggregate that has as its essential constituent the hydrous silicates of aluminum with or without free silica; it is used in commercial refractory products;

fired mold - a shell mold or solid mold that has been heated to a high temperature and is ready for casting;

flake graphite - graphitic carbon, in the form of platelets, occurring in the microstructure of gray iron;

flash - a thin section or fin of metal formed at the mold, core or die joint or parting in a casting due to the cope and drag not matching completely or where core and core print do not match;

flask - a metal or wood frame used for making and holding a sand mold; The upper part is called the cope ; the lower, the drag;

flaw - a nonspecific term often used to imply a crack like discontinuity;

floor molding - making sand molds from loose or production patterns of such size that they cannot be satisfactorily handled on a bench or molding machine, the equipment being located on the floor during the entire operation of making the mold;

flowability - a characteristic of a foundry sand mixture that enables it to move under pressure or vibration so that it makes intimate contact with all surfaces of the pattern or core box;

fluidity - the ability of liquid metal to run into and fill a mold or die cavity;

flux - (1) in metal refining, a material used to remove undesirable substances, such as sand, ash or dirt, as a molten mixture; it is also used as a protective covering for certain molten metal baths; lime or limestone is generally used to remove sand, as in iron smelting; sand, to remove iron oxide in copper refining; (2) in brazing, cutting, soldering or welding, material used to prevent the formation of or to dissolve and facilitate the removal of oxides and other undesirable substances;

foundry returns - metal in the form of gates, sprues, runners, risers and scrapped castings of known composition returned to the furnace for remelting;

free carbon - the part of the total carbon in steel or cast iron that is present in elemental form as graphite or temper carbon;

free ferrite - ferrite formed into separate grains and not intimately associated with carbides as in pearlite;

freezing range - that temperature range between liquidus and solidus temperatures in which molten and solid constituents coexist;

full mold - a trade name for an expendable pattern casting process in which the polystyrene pattern is vaporized by the molten metal as the mold is poured.

G

gassing - (1) absorption of gas by a metal; (2) evolution of gas from a metal during melting operations or upon solidification; (3) evolution of gas from an electrode during electrolysis;

gas holes - holes in castings or welds that are formed by gas escaping from molten metal as it solidifies; gas holes may occur individually, in clusters or throughout the solidified metal;

gas pocket - a cavity caused by entrapped gas;

gas porosity - fine holes or pores within a metal that are caused by entrapped gas or by the evolution of dissolved gas during solidification;

gate - the portion of the runner in a mold through which molten metal enters the mold cavity; the generic term is sometimes applied to the entire network of connecting channels that conduct metal into the mold cavity;

gated pattern - a pattern that includes not only the contours of the part to be cast but also the gates;

gating system - the complete assembly of sprues, runners and gates in a mold through which metal flows to enter the casting cavity; the term is also applied to equivalent portions of the pattern;

gooseneck - in die casting, a spout connecting a molten metal holding pot or chamber, with a nozzle or sprue hole in the die and containing a passage through which molten metal is forced on its way to the die; it is the metal injection mechanism in a hot chamber machine;

grain - an individual crystal in a polycrystalline metal or alloy; it may or may not contain twinned regions and subgrains;

grain fineness number - a system developed by the American Foundrymen's Society for rapidly expressing the average grain size of a given sand; it approximates the number of meshes per inch of that sieve that would just pass the sample;

grain refinement - the manipulation of the solidification process to cause more (and therefore smaller) grains to be formed and/or to cause the grains to form in specific shapes; the term refinement is usually used to denote a chemical addition to the metal, but can refer to control of the cooling rate;

grain refiner - any material added to a liquid metal for producing a finer grain size in the subsequent casting;

grain size - for metals, a measure of the areas or volumes of grains in a polycrystalline material, usually expressed as an average when the individual sizes are fairly uniform. In metals containing two or more phases, grain size refers to that of the matrix unless otherwise specified; grain size is reported in terms of number of grains per unit area or volume, in terms of average diameter or as a grain size number derived from area measurements;

graphite - one of the crystal forms of carbon; also the uncombined carbon in cast irons;

graphitic carbon - free carbon in steel or cast iron;

graphitization - the formation of graphite in iron or steel; where graphite is formed during solidification, the phenomenon is termed primary graphitization; where formed later by heat treatment, secondary graphitization;

gravity die casting - see permanent mold;

gray iron - cast iron that contains a relatively large percentage of the carbon present in the form of flake graphite;

green sand - a molding sand that has been tempered with water and is used for casting when still in the damp condition;

green sand core - (1) a core made of green sand and used as-rammed; (2) a sand core that is used in the unbaked condition;

green sand mold - a casting mold composed of moist prepared molding sand;

green strength - the strength of a tempered sand mixture at room temperature;

grit - crushed ferrous or synthetic abrasive material in various mesh sizes that is used in abrasive blasting equipment to clean castings;

gross porosity - in weld metal or in a casting, pores, gas holes or globular voids that are larger and in much greater numbers than those obtained in good practice;

growth (cast iron) - a permanent increase in the dimensions of cast iron resulting from repeated or prolonged heating at temperatures above 480°C (900 °F) due either to graphitizing of carbides or oxidation.

H

hardener - an alloy rich in one or more alloying elements that is added to a melt to permit closer control of composition than is possible by the addition of pure metals or to introduce refractory elements not readily alloyed with the base metal; sometimes called master alloy or rich alloy;

hearth - the bottom portions of certain furnaces, such as blast furnaces, air furnaces and other reverberatory furnaces, that support the charge and sometimes collect and hold molten metal;

heat - a stated tonnage of metal obtained from a period of continuous melting in a cupola or furnace or the melting period required to handle this tonnage;

heat-disposable pattern - a pattern formed from a wax or plastic-base material that is melted from the mold cavity by the application of heat;

holding furnace - a furnace into which molten metal can be transferred to be held at the proper temperature until it can be used to make castings;

hot box process **-** a furan resin-base process similar to shell coremaking; cores produced with it are solid unless mandrelled out;

hot chamber machine **-** a die casting machine in which the metal chamber under pressure is immersed in the molten metal in a furnace;

hot crack - a crack formed in a cast metal because of internal stress developed upon cooling following solidification; a hot crack is less open than a hot tear and usually exhibits less oxidation and decarburization along the fracture surface;

hot shortness - a tendency for some alloys to separate along grain boundaries when stressed or deformed at temperatures near the melting point; hot shortness is caused by a low-melting constituent, often present only in minute amounts, that is segregated at grain boundaries;

hot tear - a fracture formed in a metal during solidification because of hindered contraction;

hot top - (1) a reservoir, thermally insulated or heated, that holds molten metal on top of a mold for feeding of the ingot or casting as it contracts on solidifying, thus preventing the formation of pipe or voids; (2) a refractory-lined steel or iron casting that is inserted into the tip of the mold and is supported at various heights to feed the ingot as it solidifies.

I

impregnation - (1) treatment of porous castings with a sealing medium to stop pressure leaks; (2) the process of filling the pores of a sintered compact, usually with a liquid such as a lubricant; (3) the process of mixing particles of a nonmetallic substance in a matrix of metal powder, as in diamond- impregnated tools;

inclusions - particles of foreign material in a metallic matrix; the particles are usually compounds (such as oxides, sulfides or silicates), but may be of any substance that is foreign to (and essentially insoluble in) the matrix;

induction furnace - an alternating current electric furnace in which the primary conductor is coiled and generates, by electro-magnetic induction, a secondary current that develops heat within the metal charge;

induction heating or melting - heating or melting in an induction furnace;

inert gas - a gas that will not support combustion or sustain any chemical reaction, for example, argon or helium;

ingate - same as gate;

ingot - a casting of simple shape, suitable for hot working or remelting;

injection - the process of forcing molten metal into the die casting die;

injection molding - the injection of molten metal or other material under pressure into molds;

inoculant - materials that, when added to molten metal, modify the structure and thus change the physical and mechanical properties to a degree not explained on the basis of the change in composition resulting from their use;

inoculation - the addition of a material to molten metal to form nuclei for crystallization;

insert - (1) a part formed from a second material, usually a metal, that is placed in the molds and appears as an integral structural part of the final casting; (2) a removable portion of a die or mold;

insulating pads and sleeves - insulating material, such as gypsum, diatomaceous earth and so forth, used to lower the rate of solidification; as sleeves on open risers, they are used to keep the metal liquid, thus increasing the feeding efficiency;

internal shrinkage - a void or network of voids within a casting caused by inadequate feeding of that section during solidification;

internal stress - see residual stress;

inverse chill - the condition in a casting section in which the interior is mottled or white, while the other sections are gray iron; also known as reverse chill, internal chill and inverted chill;

inverse segregation - segregation in cast metal in which an excess of lower-melting constituents occurs in the earlier-freezing portions, apparently the result of liquid metal entering cavities developed in the earlier- solidified metal;

investing - the process of pouring the investment slurry into a flask surrounding the pattern to form the mold;

investment - a flowable mixture or slurry, of a graded refractory filler, a binder and a liquid vehicle that, when poured around the patterns, conforms to their shape and subsequently sets hard to form the investment mold;

investment casting - (1) casting metal into a mold produced by surrounding or investing. An expendable pattern with a refractory slurry that sets at room temperature, after which the wax or plastic pattern is removed through the use of heat prior to filling the mold with liquid metal; also called precision casting or lost wax process; (2) a part made by the investment casting process;

investment precoat - see dip coat;

investment precoat - an extremely fine investment coating applied as a thin slurry directly to the surface of the pattern to reproduce maximum surface smoothness; the coating is surrounded by a coarser, cheaper and more permeable investment to form the mold;

investment shell - ceramic mold obtained by alternately dipping a pattern set up in dip coat slurry and stuccoing with coarse ceramic particles until the shell of desired thickness is obtained.

J

jolt ramming - packing sand in a mold by raising and dropping the sand, pattern and flask on a table; jolt squeezers, jarring machines and jolt rammers are machines using this principle; also called jar ramming;

jolt-squeezer machine - a combination machine that employs a jolt action followed by a squeezing action to compact the sand around the pattern.

K

keel block - a standard test casting, for steel and other high-shrinkage alloys, consisting of a rectangular bar that resembles the keel of a boat, attached to the bottom of a large riser or shrinkhead. Keel blocks that have only one bar are often called Y-blocks; keel blocks having two bars, double keel blocks; test specimens are machined from the rectangular bar and the shrinkhead is discarded;

kiln - an oven or furnace for burning, calcining or drying a substance;

knockout - (1) removal of sand cores from a casting; (2) jarring of an investment casting mold to remove the casting and investment from the flask; (3) a mechanism for freeing formed parts from a die used for stamping, blanking, drawing, forging or heading operations; (4) a partially pierced hole in a sheet metal part, where the slug remains in the hole and can be forced out by hand if a hole is needed.

L

ladle - metal receptacle frequently lined with refractories used for transporting and pouring molten metal; types include hand, bull, crane, bottom-pour, holding, teapot, shank and lip-pour;

ladle brick - refractory brick suitable for lining ladles used to hold molten metal;

ladle coating - the material used to coat metal ladles to prevent iron pickup in aluminum alloys; the material can only consist of sodium silicate, iron oxide and water, applied to the ladle when it is heated;

ladle preheating - the process of heating a ladle prior to the addition of molten metal; this procedure reduces metal heat loss and eliminates moisture-steam safety hazards;

launder - a channel for transporting molten metal;

lining - internal refractory layer of firebrick, clay, sand or other material in a furnace or ladle;

lip-pour ladle - ladle in which the molten metal is poured over a lip, much as water is poured out of a bucket;

liquation - partial melting of an alloy, usually as a result of coring or other compositional heterogeneities;

liquation temperature - the lowest temperature at which partial melting can occur in an alloy that exhibits the greatest possible degree of segregation;

liquidus - in a phase diagram, the locus of points representing the temperatures at which the various compositions in the system begin to freeze on cooling or finish melting on heating;

loam - a molding material consisting of sand, silt and clay, used over brickwork or other structural backup material for making massive castings, usually of iron or steel;

locating boss - a boss -shaped feature on a casting to help locate the casting in an assembly or to locate the casting during secondary tooling operations;

lost foam casting (process) - an expendable pattern process in which an expandable polystyrene pattern surrounded by the unbonded sand, is vaporized during pouring of the molten metal;

lost wax process - an investment casting process in which a wax pattern is used.

M

macroshrinkage - isolated, clustered or interconnected voids in a casting that are detectable macroscopically; such voids are usually associated with abrupt changes in section size and are caused by feeding that is insufficient to compensate for solidification shrinkage;

malleable iron - a cast iron made by prolonged annealing of white iron in which decarburization, graphitization or both take place to eliminate some or all of the cementite. The graphite is in the form of temper carbon; if decarburization is the predominant reaction, the product will exhibit a light fracture surface; hence whiteheart malleable. Otherwise, the fracture surface will be dark; hence blackheart malleable; ferritic malleable has a predominantly ferritic matrix; pearlitic malleable may contain pearlite, spheroidite or tempered martensite, depending on heat treatment and desired hardness;

malleablizing - annealing white iron in such a way that some or all of the combined carbon is transformed into graphite or, in some cases, so that part of the carbon is removed completely;

master alloy - an alloy, rich in one or more desired addition elements, that is added to a melt to raise the percentage of a desired constituent;

master pattern - a pattern embodying a double contraction allowance in its construction, used for making castings to be employed as patterns in production work;

match plate - a plate of metal or other material on which patterns for metal casting are mounted (or formed as an integral part) to facilitate molding; the pattern is divided along its parting plane by the plate;

melting point - the temperature at which a pure metal, compound or eutectic changes from solid to liquid; the temperature at which the liquid and the solid are in equilibrium;

melting range - the range of temperatures over which an alloy other than a compound or eutectic changes from solid to liquid; the range of temperatures from solidus to liquidus at any given composition on a phase diagram;

metal penetration - a surface condition in castings in which metal or metal oxides have filled voids between sand grains without displacing them;

microsegregation - segregation within a grain, crystal or small particle;

microshrinkage - a casting imperfection, not detectable microscopically, consisting of interdendritic voids. Microshrinkage results from contraction during solidification where the opportunity to supply filler material is inadequate to compensate for shrinkage; alloys with wide ranges in solidification temperature are particularly susceptible;

misrun - denotes an irregularity of the casting surface caused by incomplete filling of the mold due to low pouring temperatures, gas back pressure from inadequate venting of the mold and inadequate gating;

mold - the form, made of sand, metal or refractory material, that contains the cavity into which molten metal is poured to produce a casting of desired shape;

mold cavity - the space in a mold that is filled with liquid metal to form the casting upon solidification; the channels through which liquid metal enters the mold cavity (sprue, runner, gates) and reservoirs for liquid metal (risers) are not considered part of the mold cavity proper;

mold coating - (1) coating to prevent surface defects on permanent mold castings and die castings; (2) coating on sand molds to prevent metal penetration and to improve metal finish; also called mold facing or mold dressing;

molding machine - a machine for making sand molds by mechanically compacting sand around a pattern;

molding sands - sands containing over 5% natural clay, usually between 8 and 20%;

mold jacket - wood or metal form that is slipped over a sand mold for support during pouring;

mold shift - a casting defect that results when the parts of the mold do not match at the parting line;

mold wash - an aqueous or alcoholic emulsion or suspension of various materials used to coat the surface of a mold cavity;

mottled cast iron - iron that consists of a mixture of variable proportions of gray cast iron and white cast iron; such a material has a mottled fracture appearance;

mulling - the mixing and kneading of molding sand with moisture and clay to develop suitable properties for molding.

N

naturally bonded molding sand - a sand containing sufficient bonding material as mined to be suitable for molding purposes;

no-bake binder - a synthetic liquid resin sand binder that hardens completely at room temperature, generally not requiring baking; used in a cold-setting process;

nodular graphite - graphite in the nodular form as opposed to flake form (see flake graphite); nodular graphite is characteristic of malleable iron; the graphite of nodular or ductile iron is spherulitic in form, but called nodular;

nodular iron - see preferred term ductile iron;

nominal dimension - the size of the dimension to which the tolerance is applied; for example, if a dimension is 50 mm ± 0;5 mm (2;00 in; ± 0;02 in;), the 50 mm (2;00 in;) is the nominal dimension and the ±0;5 mm (±0;02 in;) is the tolerance;

normal segregation - a concentration of alloying constituents that have low melting points in those portions of a casting that solidify last;

nozzle - (1) pouring spout of a bottom-pour ladle; (2) on a hot chamber die casting machine, the thick- wall tube that carries the pressurized molten metal from the gooseneck to the die;

nucleation - the initiation of a phase transformation at discrete sites, with the new phase growing on the nuclei;

nucleus - (1) the first structurally stable particle capable of initiating recrystallization of a phase or the growth of a new phase and possessing an interface with the parent matrix; the term is also applied to a foreign particle that initiates such action; (2) the heavy central core of an atom, in which most of the mass and the total positive electric charge are concentrated.

O

olivine - a naturally occurring mineral of the composition $(Mg,Fe)_2SiO_4$ that is crushed and used as a molding sand;

open hearth furnace - a reverberatory melting furnace with a shallow hearth and a low roof; the flame passes over the charge on the hearth, causing the charge to be heated both by direct flame and by radiation from the roof and sidewalls of the furnace;

open-sand casting - any casting made in a mold that has no cope or other covering;

oxidation - a chemical reaction in which one substance is changed to another by oxygen combining with the substance; much of the dross from holding and melting furnaces is the result of oxidation of the alloy held in the furnace;

oxidation losses - reduction in the amount of metal or alloy through oxidation; such losses are usually the largest factor in melting loss;

oxygen lance - a length of pipe used to convey oxygen either beneath or on top of the melt in a steelmaking furnace or to the point of cutting in oxygen lance cutting.

P

padding - the process of adding metal to the cross section of a casting wall, usually extending from a riser, to ensure adequate feed metal to a localized area during solidification where a shrink would occur if the added metal were not present;

particle size - the controlling lineal dimension of an individual particle, such as of sand, as determined by analysis with screens or other suitable instruments;

particle size distribution - the percentage, by weight or by number, of each fraction into which a powder or sand sample has been classified with respect to sieve number or particle size;

parting - (1) the zone of separation between cope and drag portions of the mold or flask in sand casting; (2) in the recovery of precious metals, the separation of silver from gold; (3) cutting simultaneously along two parallel lines or along two lines that balance each other in side thrust; (4) a shearing operation used to produce two or more parts from a stamping;

parting compound - a material dusted or sprayed on patterns to prevent adherence of sand and to promote easy separation of cope and drag parting surfaces when the cope is lifted from the drag;

parting line - (1) the intersection of the parting plane of a casting mold or the parting plane between forging dies with the mold or die cavity; (2) a raised line or projection on the surface of a casting or forging that corresponds to said intersection;

parting plane - (1) in casting, the dividing plane between mold halves; (2) in forging, the dividing plane between dies;

pattern - (1) a form of wood, metal or other material around which molding material is placed to make a mold for casting metals; (2) a form of wax- or plastic-base material around which refractory material is placed to make a mold for casting metals; (3) a full-scale reproduction of a part used as a guide in cutting;

pattern draft - taper allowed on the vertical faces of a pattern to permit easy withdrawal of the pattern from the mold or die;

pattern layout - a full-size drawing of a pattern showing its arrangement and structural features;

patternmaker's shrinkage - contraction allowance made on patterns to compensate for the decrease in dimensions as the solidified casting cools in the mold from the freezing temperature of the metal to room temperature; the pattern is made larger by the amount of contraction that is characteristic of the particular metal to be used;

penetration - see metal penetration;

permanent mold - a metal, graphite or ceramic mold (other than an ingot mold) that is repeatedly used for the production of many castings of the same form; liquid metal is poured in by gravity (gravity die casting);

permeability - (1) in founding, the characteristics of molding materials that permit gases to pass through them; (2) in powder metallurgy, a property measured as the rate of passage under specified conditions of a liquid or gas through a compact; (3) a general term used to express various relationships between magnetic induction and magnetizing force; these relationships are either absolute permeability, which is a change in magnetic induction divided by the corresponding change in magnetizing force or specific (relative) permeability, which is the ratio of the absolute permeability to the permeability of free space;

pinhole porosity - porosity consisting of numerous small gas holes distributed throughout the metal; found in weld metal, castings and clectrodeposited metal;

pipe - (1) the central cavity formed by contraction in metal, especially ingots, during solidification; (2) an imperfection in wrought or cast products resulting from such a cavity; (3) a tubular metal product, cast or wrought;

pit molding - molding method in which the drag is made in a pit or hole in the floor;

plaster molding - molding in which a gypsum-bonded aggregate flour in the form of a water slurry is poured over a pattern, permitted to harden and, after removal of the pattern, thoroughly dried; this technique is used to make smooth nonferrous castings of accurate size;

plunger - ram or piston that forces molten metal into a die in a die casting machine; plunger machines are those having a plunger in continuous contact with molten metal;

porosity - a characteristic of being porous, with voids or pores resulting from trapped air or shrinkage in a casting;

port - the opening through which molten metal enters the injection cylinder of a die casting plunger machine or is ladled into the injection cylinder of a cold chamber machine;

pot - (1) a vessel for holding molten metal; (2) the electrolytic reduction cell used to make such metals as aluminum from a fused electrolyte;

pouring - the transfer of molten metal from furnace to ladle, ladle to ladle or ladle into molds;

pouring basin - a basin on top of a mold that receives the molten metal before it enters the sprue or downgate;

precision casting - a metal casting of reproducible, accurate dimensions, regardless of how it is made; often used interchangeably with investment casting;

preformed ceramic core - a preformed refractory aggregate inserted in a wax or plastic pattern to shape the interior of that part of a casting which cannot be shaped by the pattern; the wax is sometimes injected around the preformed core;

pressure casting - (1) making castings with pressure on the molten or plastic metal, as in injection molding , die casting , centrifugal casting, cold chamber pressure casting and squeeze casting; (2) a casting made with pressure applied to the molten or plastic metal;

primary alloy - any alloy whose major constituent has been refined directly from core, not recycled scrap metal;

projected area - the area of a cavity or portion of a cavity, in a mold or die casting die measured from the projection on a plane that is normal to the direction of the mold or die opening.

R

ramming - (1) packing sand, refractory or other material into a compact mass; (2) the compacting of molding sand in forming a mold;

rattail - a surface imperfection on a casting, occurring as one or more irregular lines, caused by the expansion of sand in the mold;

recrystallization - a process in which the distorted grain structure of cold-worked metals is replaced by a new, strain-free grain structure during heating above a specific minimum temperature;

recrystallization temperature - the lowest temperature at which the distorted grain structure of a cold-worked metal is replaced by a new, strain-free grain structure during prolonged heating; time, purity of the metal and prior deformation are important factors;

refractory - (1) a material of very high melting point with properties that make it suitable for such uses as furnace linings and kiln construction; (2) the quality of resisting heat;

residual stress - stress present in a body that is free of external forces or thermal gradients;

reverberatory furnace - a furnace in which the flame used for melting the metal does not impinge on the metal surface itself, but is reflected off the walls of the roof of the furnace; the metal is actually melted by the generation of heat from the walls and the roof of the furnace;

rheocasting - casting of a continuously stirred semisolid metal slurry;

rigging - the engineering design, layout and fabrication of pattern equipment for producing castings; including a study of the casting solidification program, feeding and gating, risering, skimmers and fitting flasks;

riser - a reservoir of molten metal connected to a casting to provide additional metal to the casting, required as the result of shrinkage before and during solidification;

runner - (1) a channel through which molten metal flows from one receptacle to another; (2) the portion of the gate assembly of a casting that connects the sprue with the gate(s); (3) parts of patterns and finished castings corresponding to the portion of the gate assembly described in (2);

runner box - a distribution box that divides molten metal into several streams before it enters the mold cavity;

runout - (1) the unintentional escape of molten metal from a mold, crucible or furnace; (2) the defect in a casting caused by the escape of metal from the mold.

S

sag - an increase or decrease in the section thickness of a casting caused by insufficient strength of the mold sand of the cope or of the core;

sand - a granular material naturally or artificially produced by the disintegration or crushing of rocks or mineral deposits. In casting, the term denotes an aggregate, with an individual particle (grain) size of 0,06 to 2 mm (0,002 to 0,08 in;) in diameter, that is largely free of finer constituents such as silt and clay, which are often present in natural sand deposits. The most commonly used foundry sand is silica; however, zircon, olivine, alumina and other crushed ceramics are used for special applications;

sandblasting- abrasive blasting with sand;

sand casting - metal castings produced in sand molds;

sand grain distribution - variation or uniformity in particle size of a sand aggregate when properly screened by standard screen sizes;

sand reclamation - processing of used foundry sand by thermal, air or hydraulic methods so that it can be used in place of new sand without substantially changing the foundry sand practice;

sand tempering - adding sufficient moisture to molding sand to make it workable;

scab - a defect on the surface of a casting that appears as a rough, slightly raised surface blemish, crusted over by a thin porous layer of metal, under which is a honeycomb or cavity that usually contains a layer of sand; defect common to thin-wall portions of the casting or around hot areas of the mold;

scaling (scale) - surface oxidation, consisting of partially adherent layers of corrosion products, left on metals by heating or casting in air or in other oxidizing atmospheres;

screen - one of a set of sieves designated by the size of the openings, used to classify granular aggregates such as sand, ore or coke by particle size;

screen analysis - see sieve analysis;

seam - (1) a surface defect on a casting related to but of lesser degree than a cold shut ; (2) a ridge on the surface of a casting caused by a crack in the mold face;

secondary alloy - any alloy whose major constituent is obtained from recycled scrap metal;

segregation - a casting defect involving a concentration of alloying elements at specific regions, usually as a result of the primary crystallization of one phase with the subsequent concentration of other elements in the remaining liquid. Microsegregation refers to normal segregation on a microscopic scale in which material richer in an alloying element freezes in successive layers on the dendrites (coring) and in constituent network. Macrosegregation refers to gross differences in concentration (for example, from one area of a casting to another);

semipermanent mold - a permanent mold in which sand cores are used;

shakeout - removal of castings from a sand mold;

shell molding - forming a mold from thermo-setting resin-bonded sand mixtures brought in contact with preheated (150 to 260 °C or 300 to 500 °F) metal patterns, resulting in a firm shell with a cavity corresponding to the outline of the pattern; also called Croning process;

shift - a casting imperfection caused by the mismatch of cope and drag or of cores and mold;

shot - (1) small, spherical particles of metal; (2) the injection of molten metal into a die casting die; the metal is injected so quickly that it can be compared to the shooting of a gun;

shotblasting - blasting with metal shot; usually used to remove deposits or mill scale more rapidly or more effectively than can be done by sandblasting;

shrinkage - see casting shrinkage;

shrinkage cavity - a void left in cast metal as a result of solidification shrinkage;

shrinkage cracks - cracks that form in metal as a result of the pulling apart of grains by contraction before complete solidification;

sieve analysis - particle size distribution; usually expressed as the weight percentage retained on each of a series of standard sieves of decreasing size and the percentage passed by the sieve of finest size; synonymous with sieve classification;

silica - silicon dioxide (SiO_2); the primary ingredient of sand and acid refractories;

silica flour - a sand additive, containing about 99;5% silica, commonly produced by pulverizing quartz sand in large ball mills to a mesh size of 80 to 325;

skim gate - a gating arrangement designed to prevent the passage of slag and other undesirable materials into a casting;

skimming - removing or holding back dirt or slag from the surface of the molten metal before or during pouring;

skin drying - drying the surface of the mold by direct application of heat;

slag - a nonmetallic product resulting from the mutual dissolution of flux and nonmetallic impurities in smelting, refining, and certain welding operations. In steelmaking operations, the slag serves to protect the molten metal from the air and to extract certain impurities;

slag inclusion - slag or dross entrapped in a metal;

slip flask - a tapered flask that depends on a movable strip of metal to hold the sand in position. After closing the mold, the strip is retracted and the flask can be removed and reused; molds made in this manner are usually supported by a mold jacket during pouring;

slush casting - a hollow casting usually made of an alloy with a low but wide melting temperature range; after the desired thickness of metal has solidified in the mold, the remaining liquid is poured out;

snap flask - a foundry flask hinged on one corner so that it can be opened and removed from the mold for reuse before the metal is poured;

solid shrinkage - see casting shrinkage;

solidification - the change in state from liquid to solid upon cooling through the melting temperature or melting range;

solidification shrinkage - see casting shrinkage;

solidus - in a phase diagram, the locus of points representing the temperatures at which various compositions stop freezing upon cooling or begin to melt upon heating;

solute - a metal or substance dissolved in a major constituent; the component that is dissolved in the solvent;

solvent - the base metal or major constituent in a solution; the component that dissolves the solvent;

sprue - (1) the mold channel that connects the pouring basin with the runner or, in the absence of a pouring basin, directly into which molten metal is poured; sometimes referred to as downsprue or downgate; (2) sometimes used to mean all gates, risers, runners, and similar scrap that are removed from castings after shakeout;

squeeze casting - a hybrid liquid-metal forging process in which liquid metal is forced into a permanent mold by a hydraulic press;

stack molding - a molding method that makes use of both faces of a mold section, with one face acting as the drag and the other as the cope. Sections, when assembled to other similar sections, form several tiers of mold cavities and all castings are poured together through a common sprue;

stopper rod - a device in a bottom-pour ladle for controlling the flow of metal through the nozzle into a mold; the stopper rod consists of a steel rod, protective refractory sleeves and a graphite stopper head;

stopping off - filling in a portion of a mold cavity to keep out molten metal;

strainer core - a perforated core in the gating system for preventing slag and other extraneous material from entering the casting cavity;

stripping - removing the pattern from the mold or the core box from the core;

styrofoam pattern - an expendable pattern of foamed plastic, especially expanded polystyrene, used in manufacturing castings by the lost foam process;

supercooling - lowering the temperature of a molten metal below its liquidus during cooling;

superheat - any increment of temperature above the melting point of a metal; sometimes construed to be any increment of temperature above normal casting temperatures introduced for the purpose of refining, alloying or improving fluidity;

superheating - raising the temperature of molten metal above the normal melting temperature for more complete refining and greater fluidity;

supersaturated - a metastable solution in which the dissolved material exceeds the amount the solvent can hold in normal equilibrium at the temperature and other conditions that prevail;

surface area - the actual area of the surface of a casting or cavity; the surface area is always greater than the projected area;

sweep - a type of pattern that is a template cut to the profile of the desired mold shape that, when revolved around a stake or spindle, produces that shape in the mold.

T

teapot ladle - a ladle in which, by means of an external spout, metal is removed from the bottom rather than the top of the ladle;

temper - (1) to moisten green sand for casting molds with water; (2) in heat treatment, to reheat hardened steel or hardened cast iron to some temperature below the eutectoid temperature for the purpose of decreasing hardness and increasing toughness; the process is also sometimes applied to normalized steel; (3) in nonferrous alloys and in some ferrous alloys (steels that cannot be hardened by heat treatment), the hardness and strength produced by mechanical or thermal treatment or both and characterized by a certain structure, mechanical properties or reduction in area during cold working;

thermal expansion - the increase in linear dimensions of a material accompanying an increase in temperature;

thin-wall casting - a term used to define a casting that has the minimum wall thickness to satisfy its service function**;**

tie bar - a bar-shaped connection added to a casting to prevent distortion caused by uneven contraction between two separated members of the casting;

tolerance - the specified permissible deviation from a specified nominal dimension or the permissible variation in size or other quality characteristic of a part;

tramp element - contaminant in the components of a furnace charge or in the molten metal or castings, whose presence is thought to be either unimportant or undesirable to the quality of the casting; also called trace element;

transfer ladle - a ladle that can be supported on a monorail or carried in a shank and used to transfer metal from the melting furnace to the holding furnace or from the furnace to the pouring ladles;

tumbling - rotating workpieces, usually castings or forgings, in a barrel partially filled with metal slugs or abrasives, to remove sand, scale or fins; it may be done dry or with an aqueous solution added to the contents of the barrel; sometimes called rumbling or rattling;

tuyere - an opening in a cupola, blast furnace or converter for the introduction of air or inert gas.

U

undercooling - same as supercooling**;**

undercut - a recess having an opening smaller than the internal configuration, thus preventing the mechanical removal of a one-piece core.

V

vacuum arc remelting - a consumable-electrode remelting process in which heat is generated by an electric arc between the electrode and the ingot. The process is performed inside a vacuum chamber; exposure of the droplets of molten metal to the reduced pressure reduces the amount of dissolved gas in the metal; sometimes abbreviated VAR;

vacuum casting - a casting process in which metal is melted and poured under very low atmospheric pressure; a form of permanent mold casting in which the mold is inserted into liquid metal, vacuum is applied and metal is drawn up into the cavity;

vacuum degassing - the use of vacuum techniques to remove dissolved gases from molten alloys;

vacuum induction melting - a process for remelting and refining metals in which the metal is melted inside a vacuum chamber by induction heating; the metal can be melted in a crucible and then poured into a mold; sometimes abbreviated VIM;

vacuum melting - melting in a vacuum to prevent contamination from air and to remove gases already dissolved in the metal; the solidification can also be carried out in a vacuum or at low pressure;

vacuum molding - see V process;

vacuum refining - melting in a vacuum to remove gaseous contaminants from the metal;

vent - a small opening or passage in a mold or core to facilitate the escape of gases when the mold is poured;

vermicular iron - same as compacted graphite iron;

void - a shrinkage cavity produced in castings during solidification;

V process - a molding process in which the sand is held in place in the mold by vacuum; the mold halves are covered with a thin sheet of plastic to retain the vacuum.

W

warpage - deformation other than contraction that develops in a casting between solidification and room temperature; also the distortion that occurs during annealing, stress relieving and high- temperature service;

wash - (1) a coating applied to the face of a mold prior to casting; (2) an imperfection at a cast surface similar to a cut (3);

wax pattern - a precise duplicate, allowing for shrinkage, of the casting and required gates, usually formed by pouring or injecting molten wax into a die or mold;

white iron - cast iron that shows a white fracture because the carbon is in combined form.

Y

yield - comparison of casting weight to the total weight of metal poured into the mold.

Z

zircon - the mineral zircon silicate ($ZrSiO_4$), a very high melting point acid refractory material used as a molding sand;

zone melting - highly localized melting, usually by induction heating, of a small volume of an otherwise solid piece, usually a rod. By moving the induction coil along the rod, the melted zone can be transferred from one end to the other; in a binary mixture where there is a large difference in composition on the liquidus and solidus lines, high purity can be attained by concentrating one of the constituents in the liquid as it moves along the rod.

REFERENCE

1. 36th-45th Census of World Casting Production. Modern Casting 12 (2001-2011).
2. 45th Census of World Casting Production. Modern Casting 12 (2016), 16-19.
3. Analysis of Casting Defects, AFS, Des Plaines, IL, 1974.
4. Ashby M.F., Material Selection in Mechanical Design, Butterworth-Heinemann, 1999.
5. ASM Handbook Volume 15: Casting - ASM International.
6. ASM Handbook, Vol. 15, Casting, 2008, "History and Trends of Metal Casting," pp. 3–15.
7. Baron C., Bartocha D., and Szajnar J. (2007). The determination of the thickness of composite layer for ball casting. Archives of Materials Science and Engineering, 28(7): 425-428. [Google Scholar].
8. Bawa H.S., Manufacturing processes -II. New York: Tata McGraw-Hill Education; 2004.
9. Beeley P.R. Foundry technology. Butterworth-Heinemann; 2001.
10. Booth G.N., "Defining Quality through SPC: Foundry Applications,"Modern Casting, 75: 27–32, May 1985.
11. Bralla J.B., Design for manufacturability handbook, McGraw Hill handbooks, 2nd edition, New york.
12. Büchner H.J., World Casting Production – Forecast 2011. Düsseldorf April, 7, 2011.
13. Buhr R.K., Warda R.D., Whiting L.V., Davis K.G., and Sahoo M., The State of Foundry Technology as Measured by a Mobile Foundry, Transactions of American Foundrymen's Society, 96: 171–182, 1988.
14. Butler W.A., Timelli G., Battaglia E., Bonollo F., Die Casting (Permanent Mold). Ref. Module Mater. Science Mater. Eng., Elsevier; 2016.
15. CAEF Committee of Associations of European Foundries (Information materials).
16. Campbell J., Casting, Butterworth-Heinemann, 2003.
17. Campbell J.S., Principles Of Manufacturing Materials And Processes, Tata McGraw Hill, 1995.
18. Casting Copper-Base Alloys, edited by Ducharme S., Sahoo M.and Sadayappan K. 2d ed., Schaumburg, IL, 2007.

19. Casting Defects Handbook: Aluminum & Aluminum Alloys, AFS, Schaumburg, IL, 2011.

20. Casting Defects Handbook: Copper and Copper-Base Alloys, AFS, Schaumburg, IL, 2010.

21. Casting Defects Handbook: Iron and Steel, AFS, Schaumburg, IL, 2008.

22. Chhabra M, Singh R., Experimental investigation of pattern-less casting solution using additive manufacturing technique. MIT Int J Mech Eng. 2011;1:17–25.

23. Chirita G., Soares D., Silva F.S., Advantages of the centrifugal casting technique for the production of structural components with Al–Si alloys. Mater Des. 2008;29:20–7.

24. Dańko J., Holtzer M., Metalurgija 45 (2006) 4, 333-340.

25. Danylchenko L., Yousif Duhair. Investigation of machining parameters in the design of CNC technologies / Book of abstract of the International scientific and technical student's conference "Fundamental and applied sciences. Actual guestions" 26th-27th of April 2018. – Ternopil: TNTU, 2018. – P. 203-204.

26. Danylchenko, L., Radyk, D. Features of introduction the additive technologies in workpieces' manufacturing processes. In: Preceeding of the International Scientific and Technical Conference dedicated to the memory of Prof. Hevko B. "Problems of design theory and manufacture of transport and technological machines", Ternopil, Ukraine, September 2021. Ternopil: TNTU, pp. 26-27.

27. Danylchenko L.M., Radyk D.L., Research of methods of strengthening of parts by surface plastic deformation / Book of abstract of the XX-th scientific conference of Ternopil Ivan Pul'uj National Technical University 17th-18th of May 2017. – Ternopil: TNTU, 2019. – P. 21.

28. Danylchenko L.M., Shushkevych O.Y., Research of technological methods of strengthening the surffce layer of details of machines / Book of abstract of the International scientific and technical student's conference "Fundamental and applied sciences. Actual guestions" 25th-26th of April 2017. – Ternopil: TNTU, 2017. – P. 157-158.

29. Degarmo E. Paul, Black J.T., Kohser Ronald A., Materials and processes in manufacturing, John Wiley and sons, 8th edition, 1999

30. Deter G.E., Engineering Design, McGraw-Hill,1999.

31. Dieter G.E., Mechanical Metallurgy, McGraw-Hill, 1961.

32. Enright T.P., "Statistical Methods Reduce Casting Defects," Modern Casting, 78: 51–52, Nov. 1988.

33. Foster J., "The Iron Age Moulds From Gussage All Saints," Occasional Paper No. 12, British Museum, London, 1980.

34. Gawronski J., Szajna J., and Wróbel P. (2004). Study on theoretical bases of receiving composite alloy layers on surface of cast steel castings. Journal of Materials Processing Technology, 157: 679-682. https://doi.org/10.1016/j.jmatprotec.2004.07.153/ [Google Scholar].

35. Ghomashchi M.R., Vikhrov A., Squeeze casting: an overview. J. Mater Process Technol. 2000;101:1–9.

36. Ghosh A. and Mallik A.K., Manufacturing Science, Affiliated East-West Press Private Limited, New Delhi, 2001.

37. Greer S.E., A comparison of the ancient metal casting materials and processes to modern metal casting materials and processes. Hartford, Connecticut: Master of Mechanical Engineering. Rensselaer Polytechnic Institute; 2009.

38. Groover M.P., Fundamentals of modern manufacturing: materials, processes, and systems. Hoboken: Wiley; 2010.

39. Haga T. and Takahashi K. (2004). Downward melt drag twin roll caster. Journal of Materials Processing Technology, 157: 706-711. https://doi.org/10.1016/j.jmatprotec.2004.07.129. [Google Scholar].

40. Heijkoop T. and Sare I.R. (1989). Cast-bonding - A new process for manufacturing composite wear products. Cast Metals, 2(3): 160-168. https://doi.org/10.1080/09534962.1989.11818997. [Google Scholar].

41. Heine R.W., Loper C.R., Rosenthal Jr., and P.C., Principles of Metal Casting, McGraw-Hill Book Company, New York, 1967.

42. International Atlas of Casting Defects, AFS, Des Plaines, IL, 1999.

43. Kalpakjian S., Schmid S.R., Manufacturing Processes for Engineering Materials, Pearson education, 2009.

44. Kalpakjian S., Schmid S., Manufacturing engineering & technology. 7 ed. Upper Saddle River: Prentice Hall; 2013.

45. Krouth T.J. Foundry tooling and metal castings in days. Proceedings of international conference worldwide advances in rapid and high-performance tooling, EuroMold, Frankfurt/M, Germany; 2002.

46. Kurt B. and Calik A. (2009). Interface structure of diffusion bonded duplex stainless steel and medium carbon steel couple. Materials Characterization, 60(9): 1035-1040. https://doi.org/10.1016/j. matchar.2009.04.011. [Google Scholar].

47. Kurt B., Orhan N., and Hasçalık A. (2007). Effect of high heating and cooling rate on interface of diffusion bonded gray cast iron to medium

carbon steel. Materials and Design, 28(7): 2229-2233. https://doi.org/10.1016/j.matdes.2006.06.002. [Google Scholar].

48. Li C., Wei Z., Chenhong W., Baochang J., Qingchun X., Application of digital pattern-less molding technology to produce art casting. Research and Development, China Foundry 2014;11.

49. "Lost Foam Casting," chapter by Q. Han, C. Song, and M. Marlatt, Technology for Magnesium Production: Design, Products and Applications, M. Sahoo (as principal author), American Foundry Society, 2011, pp. 161–182.

50. Magendran Parashar B.S. & R.K. Mittal, "Elements of Manufacturing Processes", Prentice Hall of India, 2003.

51. Manual of Casting Defects, 2d ed., S&B Industrial Minerals, GMBH, Marl, Germany, 2006.

52. Marukovich E.I., Branovitsky A.M., Na Y.S., Lee J.H., and Choi K.Y. (2006). Study on the possibility of continuous-casting of bimetallic components in condition of direct connection of metals in a liquid state. Materials and Design, 27(10): 1016-1026. https://doi.org/10.1016/j.matdes.2005.02.007. [Google Scholar].

53. Mold and Core Test Handbook. American Foundrymen's Society; 1978.

54. Nerl C., Wimmer M., Hoffmann H., Kaschnitz E., Langbein F., and Volk W. (2014). Development of a continuous composite casting process for the production of bilayer aluminium strips. Journal of Materials Processing Technology, 214(7): 1445-1455. https://doi.org/10.1016/j.jmatprotec.2014.02.018. [Google Scholar].

55. Pandey P.C. and Singh C.K., Production Engineering Sciences, Standard Publishers Ltd., 2003.

56. Pattnaik S, Karunakar DB, Jha PK. Developments in investment casting process—a review. J Mater Process Technol. 2012;212:2332-48. doi:10.1016/j.jmatprotec.2012.06.003.

57. Peterson M.B. and Winer W.O. (1980). Wear control handbook. American Society of Mechanical Engineers, New York City, USA. [Google Scholar].

58. Pribulova A., Mihok L., Lastivka A., Archives of Foundry Engineering 20 (2006), 93-100.

59. Pylypets, M., Danylchenko, L. (2019). Simulation modeling in designing applications for sheet metal forming. In: Preceeding of the XXI-th scientific conference of Ternopil Ivan Pul'uj National Technical University, Ternopil, Ukraine, May 2019. Ternopil: TNTU, pp. 13-14.

60. Rajkolhe R., Khan J.G., Defects, causes and their remedies in casting process: a review. Int. J. Res. Advent. Technol. 2014; 2:2321–963.
61. Ramadan M. (2018). Interface structure and elements diffusion of as-cast and annealed ductile iron/stainless steel bimetal castings. Engineering, Technology and Applied Science Research, 8(2): 2709-2714. [Google Scholar].
62. Rao P.N., “Manufacturing Technology”, 2nd Edition, Tata McGraw-Hill Publishing Limited, 2002.
63. Ravi B., Metal casting: computer-aided design and analysis. PHI Learning Pvt. Ltd.; 2005.
64. Rundman K.B., Metal casting. Dep Mater Sc. Eng. Mich. Technol. Univ Michagan 2000:17–9. 22.
65. Schey J.A., Introduction to manufacturing processes. New York: McGraw-Hill; 1987.
66. Schey John A., Introduction to Manufacturing Processes, Mcgraw Hill, 3rdEdition, 2000.
67. Sharma P.C., A Text Book of Production Technology, 4th Edition, S. Chand and Company, 2003.
68. Simpson B.L., History of the metal-casting industry. 2nd ed. Revised ed. American Foundrymen’s Society; 1969.
69. Simpson B.L., Development of the Metal Castings, Industry, American Foundrymen's Association, Chicago, 1948.
70. Singh .R, Singh J.P., Comparison of rapid casting solutions for lead and brass alloys using three-dimensional printing. Proc. Inst. Mech. Eng. Part C.J. Mech. Eng. Sc. 2009; 223:2117–23.
71. Singh J.P., Singh R., Investigations for a statistically controlled rapid casting solution of lead alloys using three-dimensional printing. Proc. Inst. Mech. Eng. Part C.J. Mech. Eng. Sc. 2009; 223:2125–34.
72. Singh R, Singh JP. Comparison of rapid casting solutions for lead and brass alloys using three-dimensional printing. Proc Inst Mech Eng Part C J Mech Eng Sci. 2009;223:2117-23. doi:10.1243/09544062JMES1387.
73. Smith C.S., The Early History of Casting, Molds, and the Science of Solidification, in A Search for Structure: Selected Essays on Science, Art, and History, MIT Press, Cambridge, MA and London, 1981, p 127-173.
74. Spada K., Modern Casting: Annual Census of Casting Production, 47th Census of World Casting Production, December 2013, pp. 18–23.
75. Swift K.G., Booker J.D., Chapter 3 - Casting processes. In: Booker KGSD, Manuf. Process Sel. Handb., Oxford: Butterworth-Heinemann; 2013, p. 61–91.

76. Vasylkiv V.V., Radyk D.L., Danylchenko L.M., Methodical instructions for practice work № 1 on the topic: "Research of the use of additive technologies in modern enterprises" in the course "Innovative technologies in mechanical engineering". - Ternopil, 2021. - 11 p.

77. V. Vasylkiv, M. Pylypets, L. Danylchenko, D. Radyk. Use of computer-integrated technologies in training of engineering specialists. In: Ternopil National Ivan Puluj Technical University, Proceedings of the International Conference Advanced Applied Energy and Information Technologies, Ternopil, December 15-17, 2021, pp. 74-80.

78. Zum Gahr K.H. (1987). Microstructure and wear of materials. Vol. 10, Elsevier, Amsterdam, Netherlands. [Google Scholar].