



Handbook of Metalworking and Casting Engineering

Sharolyn Edmonds

Nikita Laws

First Edition, 2012

ISBN 978-81-323-0921-5

© All rights reserved.

Published by:
Academic Studio
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter 1 - Metalworking

Chapter 2 - Foundry

Chapter 3 - Polishing and Planing (shaping)

Chapter 4 - Parts Cleaning

Chapter 5 - Hot Working and Hot Pressing

Chapter 6 - Forge

Chapter 7 - Cutting Fluid

Chapter 8 - Architectural Metals and Mass Finishing

Chapter 9 - Casting (Metalworking)

Chapter 10 - Riser (Casting) & Chill (Casting)

Chapter 11 - Full-Mold Casting & Semi-Solid Metal Casting

Chapter 12 - Permanent Mold Casting

Chapter 13 - Sand Casting

Chapter 14 - Continuous Casting & Lost-Foam Casting

Chapter 15 - Plaster Mold Casting & Shell Molding

Chapter-1

Metalworking



Machining a bar of metal on a lathe.

Metalworking is the process of working with metals to create individual parts, assemblies, or large scale structures. The term covers a wide range of work from large ships and bridges to precise engine parts and delicate jewelry. It therefore includes a correspondingly wide range of skills, processes, and tools.

Metalworking is a science, art, hobby, industry and trade. Its historical roots span cultures, civilizations, and millennia. Metalworking has evolved from the discovery of smelting various ores, producing malleable and ductile metal useful for tools and adornments. Modern metalworking processes, though diverse and specialized, can be

categorized as forming, cutting or joining processes. Today's machine shop includes a number of machine tools capable of creating a precise, useful workpiece.

Prehistory

Metalworking predates history. No one knows with any certainty where or when metalworking began. The earliest technologies were impermanent and were unlikely to leave evidence for long. The advance that brought metal into focus was the connection of fire and metals. Who accomplished this is as unknown as the when and where, but the Egyptians are thought to have been one of the first civilizations to work gold.

Not all metal required fire to obtain it or work it. Isaac Asimov speculated that gold was the "first metal." His reasoning is that gold by its chemistry is found in nature as nuggets of pure gold. In other words, gold, as rare as it is, is always found in nature as the metal that it is. There are a few other metals that sometimes occur natively, and as a result of meteors. Almost all other metals are found in ores, a mineral bearing rock, that require heat or some other process to liberate the metal. Another feature of gold is that it is workable as it is found, meaning that no technology beyond eyes to find a nugget and a hammer and an anvil to work the metal is needed. Stone hammer and stone anvil will suffice for technology. This is the result of gold's properties of malleability and ductility. The earliest tools were stone, bone, wood, and sinew. They sufficed to work gold.

At some unknown point the connection between heat and the liberation of metals from rock became clear, rocks rich in copper, tin, and lead came into demand. These ores were mined wherever they were recognized. Remnants of such ancient mines have been found all over what is today the Middle East. Metalworking was being carried out by the South Asian inhabitants of Mehrgarh between 7000–3300 BCE. The end of the beginning of metalworking occurs sometime around 6000 BCE when copper smelting became common in the Middle East.

The ancients knew of seven metals. Here they are arranged in order of their oxidation potential:

- Iron +0.44,
- Tin +0.14
- Lead +0.13
- Copper -0.34
- Mercury -0.79
- Silver -0.80
- Gold -1.50

The oxidation potential is important because it is one indicator of how tightly bound to the ore the metal is likely to be. As can be seen, iron is significantly higher than the other six metals while gold is dramatically lower than the six above it. Gold's low oxidation is one of the main reasons that gold is found in nuggets. These nuggets are relatively pure gold and are workable as they are found.

Copper ore, being relatively abundant, and tin ore became the next important players in the story of metalworking. Using heat to smelt copper from ore, a great deal of copper was produced. It was used for both jewelry and simple tools. However, copper by itself was too soft for tools requiring edges and stiffness. At some point tin was added into the molten copper and bronze was born. Bronze is an alloy of copper and tin. Bronze was an important advance because it had the edge-durability and stiffness that pure copper lacked. Until the advent of iron, bronze was the most advanced metal for tools and weapons in common use.

Looking beyond the Middle East, these same advances and materials were being discovered and used the world around. China and Britain jumped into the use of bronze with little time being devoted to copper. Japan began the use of bronze and iron almost simultaneously. In the Americas things were different. Although the peoples of the Americas knew of metals, it wasn't until the arrival of Europeans that metal for tools and weapons took off. Jewelry and art were the principal uses of metals in the Americas prior to European influence.

Around the date 2700 BCE, production of bronze was common in locales where the necessary materials could be assembled for smelting, heating, and working the metal. Iron was beginning to be smelted. Iron began its emergence as an important metal for tools and weapons. The Iron Age was dawning.

History



A turret lathe operator machining parts for transport planes at the Consolidated Aircraft Corporation plant, Fort Worth, Texas, USA in the 1940s.

By the historical periods of the Pharaohs in Egypt, the Vedic Kings in India, the Tribes of Israel, and the Mayan Civilization in North America, among other ancient populations, precious metals began to have value attached to them. In some cases rules for ownership, distribution, and trade were created, enforced, and agreed upon by the respective peoples. By the above periods metalworkers were very skilled at creating objects of adornment, religious artifacts, and trade instruments of precious metals (non-ferrous), as well as weaponry usually of ferrous metals and/or alloys. These skills were finely honed and well executed. The techniques were practiced by artisans, blacksmiths, atharvavedic practitioners, alchemists, and other categories of metalworkers around the globe. For example, the ancient technique of granulation is found around the world in numerous ancient cultures before the historic record shows people traveled seas or overland to far regions of the earth to share this process that still being used by metalsmiths today.

As time progressed metal objects became more common, and ever more complex. The need to further acquire and work metals grew in importance. Skills related to extracting metal ores from the earth began to evolve, and metalsmiths became more knowledgeable. Metalsmiths became important members of society. Fates and economies of entire

civilizations were greatly affected by the availability of metals and metalsmiths. The metalworker depends on the extraction of precious metals to make jewelry, build more efficient electronics, and for industrial and technological applications from construction to shipping containers to rail, and air transport. Without metals, goods and services would cease to move around the globe on the scale we know today.

More individuals than ever before are learning metalworking as a creative outlet in the forms of jewelry making, hobby restoration of aircraft and cars, blacksmithing, tinsmithing, tinkering, and in other art and craft pursuits. Trade schools continue to teach welding in all of its forms, and there is a proliferation of schools of Lapidary and Jewelers arts and sciences at this- the beginning of the 21st Century AD.

General metalworking processes



A combination square used for transferring designs.



A caliper is used to precisely measure a short length.

Metalworking generally is divided into the following categories, *forming*, *cutting*, and, *joining*. Each of these categories contain various processes.

Compatibility chart of materials versus processes									
	Material								
Process	Iron	Steel	Aluminium	Copper	Magnesium	Nickel	Refractory metals	Titanium	Zinc
Sand casting	X	X	X	X	X	X			0
Permanent mold casting	X	0	X	0	X	0			0
Die casting			X	0	X				X
Investment casting		X	X	X	0	0			
Closed-die forging		X	0	0	0	0	0	0	
Extrusion		0	X	X	X	0	0	0	
Cold heading		X	X	X		0			
Stamping		X	X	X	0	X		0	0

& deep drawing									
Screw machine	0	X	X	X	0	X	0	0	0
Powder metallurgy	X	X	0	X		0	X	0	
Key: X = Routinely performed, 0 = Performed with difficulty, caution, or some sacrifice, blank = Not recommended									

Prior to most operations, the metal must be marked out and/or measured, depending on the desired finished product.

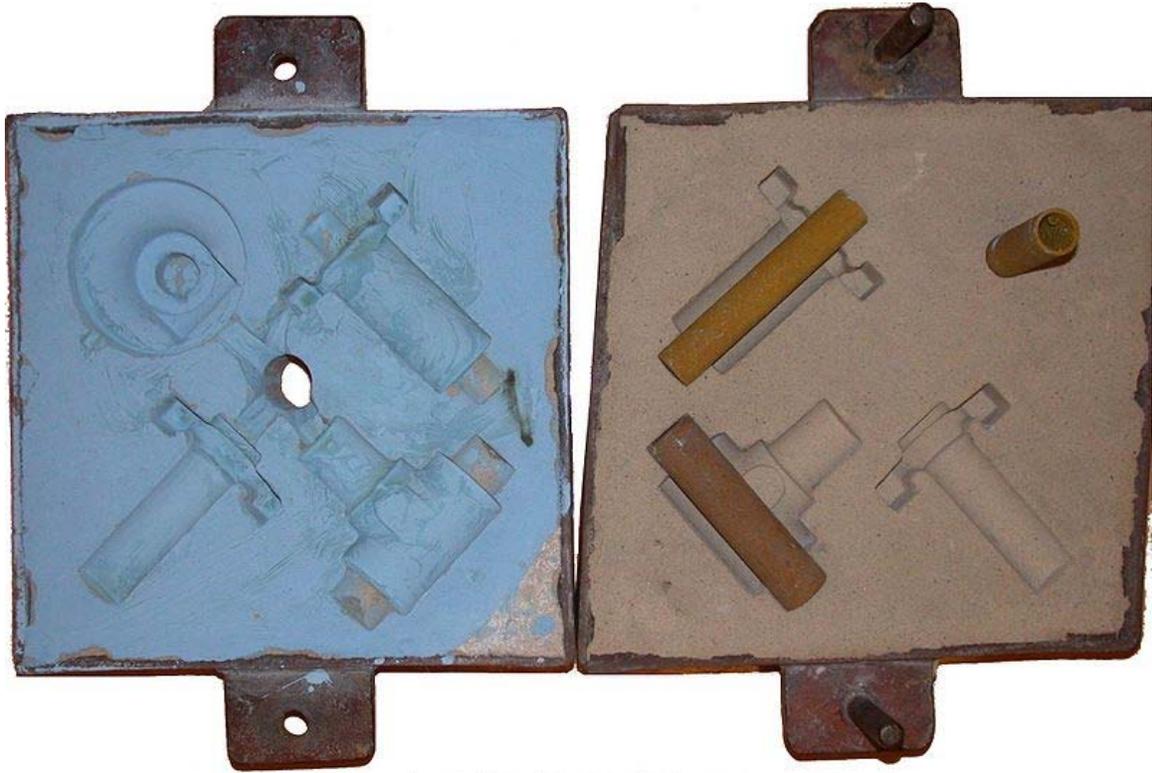
Marking out (also known as layout) is the process of transferring a design or pattern to a workpiece and is the first step in the handcraft of metalworking. It is performed in many industries or hobbies, although in the repetition industries the need to mark out every individual piece is eliminated. In the metal trades area, marking out consists of transferring the engineer's plan to the workpiece in preparation for the next step, machining or manufacture.

Calipers are hand tools designed to precisely measure the distance between two points. Most calipers have two sets of flat, perpendicular edges used for inner or outer diameter. These calipers can be accurate to within one-thousandth of an inch (25.4µm). Different types of calipers have different mechanisms for displaying the distance measured. Where larger objects need to be measured with less precision, a tape measure is often used.

Forming processes

These *forming* processes modify metal or workpiece by deforming the object, that is, without removing any material. Forming is done with heat and pressure, or with mechanical force, or both.

Casting



A sand casting mold

Casting achieves a specific form by pouring molten metal into a mold and allowing it to cool, with no mechanical force. Forms of casting include:

- Investment casting (called lost wax casting in art)
- Centrifugal casting
- Die casting
- Sand casting
- Shell casting
- Spin casting

Plastic deforming



A red-hot metal workpiece is inserted into a forging press.

Plastic deformation involves using heat or pressure to make a workpiece more conductive to mechanical force. Historically, this and casting were done by blacksmiths, though today the process has been industrialized.

- Cold sizing
- Extrusion
- Forging
- Hot metal gas forming
- Powder metallurgy

- Friction drilling

Sheet metal forming



A metal spun brass vase

These types of forming process involve the application of mechanical force at room temperature.

- Bending
- Coining
- Decambering
- Deep drawing

- Drawing
- Spinning
- Flow turning
- Raising
- Roll forming
- Roll bending
- Repoussé and chasing
- Rolling
- Rubber pad forming
- Shearing
- Stamping
- Wheeling using an English wheel (wheeling machine)

Cutting processes



A CNC plasma cutting machining

Cutting is a collection of processes wherein material is brought to a specified geometry by removing excess material using various kinds of tooling to leave a finished part that meets specifications. The net result of cutting is two products, the waste or excess material, and the finished part. If this were a discussion of woodworking, the waste would be sawdust and excess wood. In cutting metals the waste is chips or swarf and excess metal. These processes can be divided into chip producing cutting, generally

known as machining. Burning or cutting with an oxyfuel torch is a welding process not machining. There are also miscellaneous specialty processes such as chemical milling.

Cutting is nearly fully represented by:

- Chip producing processes most commonly known as machining
- Burning, a set of processes which cut by oxidizing a kerf to separate pieces of metal
- Specialty processes

Drilling a hole in a metal part is the most common example of a chip producing process. Using an oxy-fuel cutting torch to separate a plate of steel into smaller pieces is an example of burning. Chemical milling is an example of a specialty process that removes excess material by the use of etching chemicals and masking chemicals.

There are many technologies available to cut metal, including:

- Manual technologies: saw, chisel, shear or snips
- Machine technologies: turning, milling, drilling, grinding, sawing
- Welding/burning technologies: burning by laser, oxy-fuel burning, and plasma
- Erosion technologies: by water jet or electric discharge.

Cutting fluid or coolant is used where there is significant friction and heat at the cutting interface between a cutter such as a drill or an end mill and the workpiece. Coolant is generally introduced by a spray across the face of the tool and workpiece to decrease friction and temperature at the cutting tool/workpiece interface to prevent excessive tool wear. In practice there are many methods of delivering coolant.

Machining



A milling machine in operation, including coolant hoses.

Milling is the complex shaping of metal or other materials by removing material to form the final shape. It is generally done on a milling machine, a power-driven machine that in its basic form consists of a milling cutter that rotates about the spindle axis (like a drill), and a worktable that can move in multiple directions (usually two dimensions [x and y axis] relative to the workpiece). The spindle usually moves in the z axis. It is possible to raise the table (where the workpiece rests). Milling machines may be operated manually or under computer numerical control (CNC), and can perform a vast number of complex operations, such as slot cutting, planing, drilling and threading, rabbeting, routing, etc. Two common types of mills are the horizontal mill and vertical mill.

The pieces produced are usually complex 3D objects that are converted into x, y, and z coordinates that are then fed into the CNC machine and allow it to complete the tasks required. The milling machine can produce most parts in 3D, but some require the objects to be rotated around the x, y, or z coordinate axis (depending on the need). Tolerances are

usually in the thousandths of an inch (Unit known as Thou), depending on the specific machine.

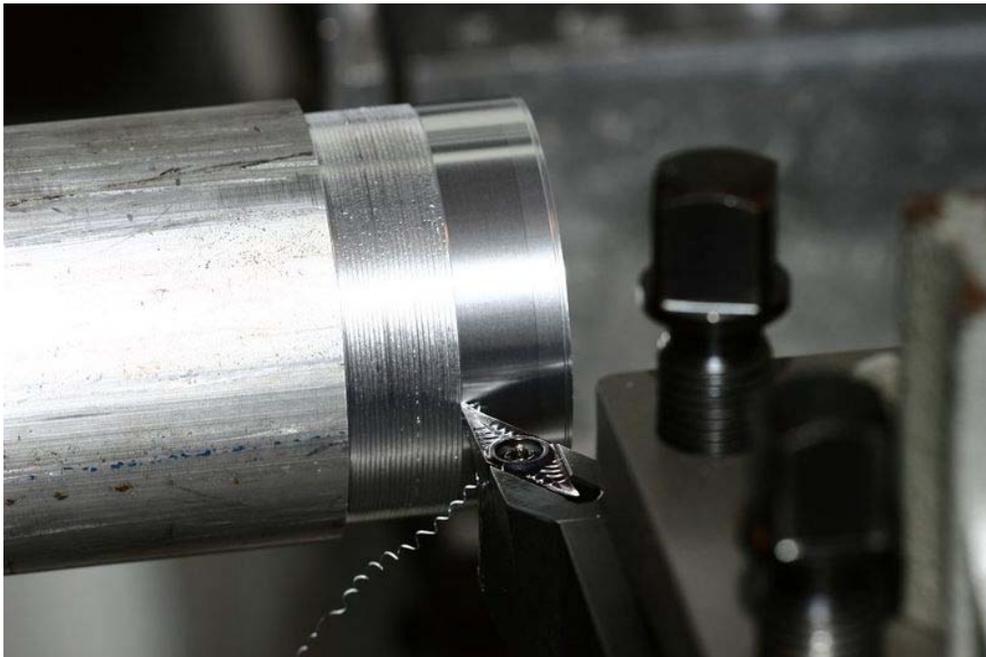
In order to keep both the bit and material cool, a high temperature coolant is used. In most cases the coolant is sprayed from a hose directly onto the bit and material. This coolant can either be machine or user controlled, depending on the machine.

Materials that can be milled range from aluminum to stainless steel and most everything in between. Each material requires a different speed on the milling tool and varies in the amount of material that can be removed in one pass of the tool. Harder materials are usually milled at slower speeds with small amounts of material removed. Softer materials vary, but usually are milled with a high bit speed.

The use of a milling machine adds costs that are factored into the manufacturing process. Each time the machine is used coolant is also used, which must be periodically added in order to prevent breaking bits. A milling bit must also be changed as needed in order to prevent damage to the material. Time is the biggest factor for costs. Complex parts can require hours to complete, while very simple parts take only minutes. This in turn varies the production time as well, as each part will require different amounts of time.

Safety is key with these machines. The bits are traveling at high speeds and removing pieces of usually scalding hot metal. The advantage of having a CNC milling machine is that it protects the machine operator.

Turning



A lathe cutting material from a workpiece.

Turning is a metal cutting process for producing a cylindrical surface with a single point tool. The workpiece is rotated on a spindle and the cutting tool is fed into it radially, axially or both. Producing surfaces perpendicular to the workpiece axis is called facing. Producing surfaces using both radial and axial feeds is called profiling.

A *lathe* is a machine tool which spins a block or cylinder of material so that when abrasive, cutting, or deformation tools are applied to the workpiece, it can be shaped to produce an object which has rotational symmetry about an axis of rotation. Examples of objects that can be produced on a lathe include candlestick holders, table legs, bowls, baseball bats, crankshafts, camshafts, and bearing mounts.

Lathes have three main components: the headstock, the carriage, and the tailstock. The headstock's spindle secures the workpiece with a chuck, whose jaws (usually three or four) are tightened around the piece. The spindle rotates at high speed, providing the energy to cut the material. While historic lathes were powered by belts from the ceiling, modern examples use electric motors. The workpiece extends out of the spindle along the axis of rotation above the flat bed. The carriage is a platform that can be moved, precisely and independently, horizontally parallel and perpendicular to the axis of rotation. A hardened cutting tool is held at the desired height (usually the middle of the workpiece) by the toolpost. The carriage is then moved around the rotating workpiece, and the cutting tool gradually shaves material from the workpiece. The tailstock can be slid along the axis of rotation and then locked in place as necessary. It may hold centers to further secure the workpiece, or cutting tools driven into the end of the workpiece.

Other operations that can be performed with a single point tool on a lathe are:

Chamfering: Cutting an angle on the corner of a cylinder.

Parting: The tool is fed radially into the workpiece to cut off the end of a part.

Threading: A tool is fed along and across the outside or inside surface of rotating parts to produce external or internal threads.

Boring: A single-point tool is fed linearly and parallel to the axis of rotation.

Drilling: Feeding the drill into the workpiece axially.

Knurling: Produces a regular cross-hatched pattern in work surfaces intended to be gripped by hand.

Modern computer numerical control (CNC) lathes and (CNC) machining centres can do secondary operations like milling by using driven tools. When driven tools are used the work piece stops rotating and the driven tool executes the machining operation with a rotating cutting tool. The CNC machines use x, y, and z coordinates in order to control the turning tools and produce the product. Most modern day CNC lathes are able to produce most turned objects in 3D.

Materials appropriate for turning used are softer metals, although harder metals can be turned with a bit more time and effort.

The turning tool material must be harder than the material being turned in order for the process to work. Production rates for this process depend on the object being turned and the speed at which it can be done. More complex materials, therefore, will take more time.

Threading



Three different types and sizes of taps.

There are many threading processes including: cutting threads with a tap or die, thread milling, single-point thread cutting, thread rolling and forming, and thread grinding. A *tap* is used to cut a female thread on the inside surface of a pre-drilled hole, while a *die* cuts a male thread on a preformed cylindrical rod.

Grinding



A surface grinder

Grinding uses an abrasive process to remove material from the workpiece. A **grinding machine** is a machine tool used for producing very fine finishes, making very light cuts, or high precision forms using an abrasive wheel as the cutting device. This wheel can be made up of various sizes and types of stones, diamonds or inorganic materials.

The simplest grinder is a bench grinder or a hand-held angle grinder, for deburring parts or cutting metal with a zip-disc.

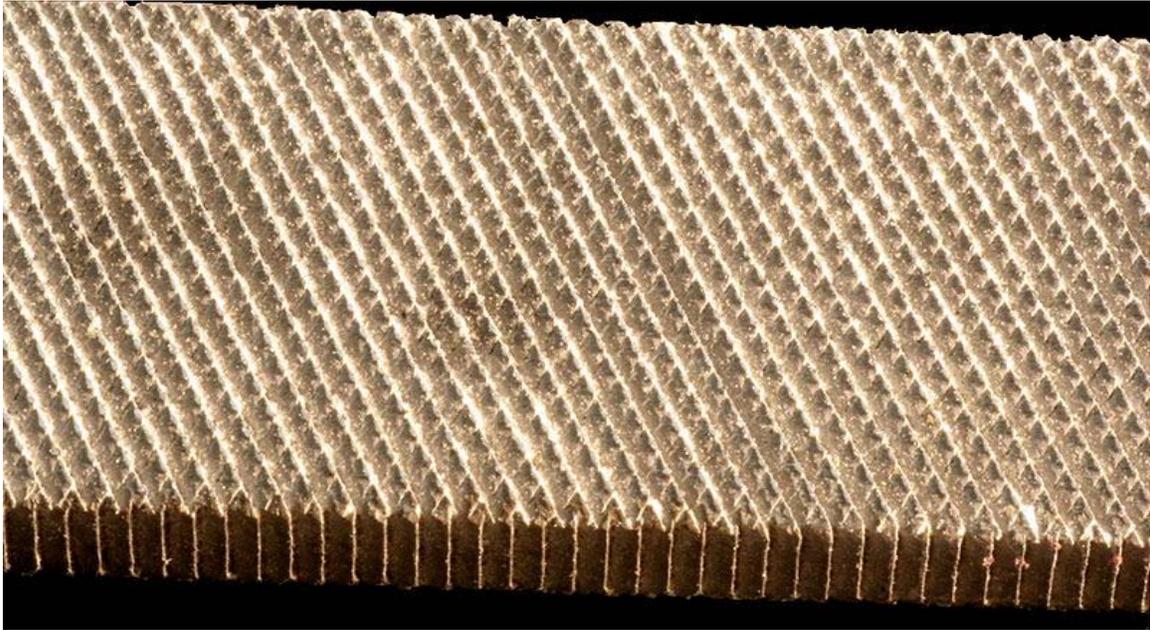
Grinders have increased in size and complexity with advances in time and technology. From the old days of a manual toolroom grinder sharpening endmills for a production shop, to today's 30000 RPM CNC auto-loading manufacturing cell producing jet turbines, grinding processes vary greatly.

Grinders need to be very rigid machines to produce the required finish. Some grinders are even used to produce glass scales for positioning CNC machine axis. The common rule is the machines used to produce scales be 10 times more accurate than the machines the parts are produced for.

In the past grinders were used for finishing operations only because of limitations of tooling. Modern grinding wheel materials and the use of industrial diamonds or other man-made coatings (cubic boron nitride) on wheel forms have allowed grinders to achieve excellent results in production environments instead of being relegated to the back of the shop.

Modern technology has advanced grinding operations to include CNC controls, high material removal rates with high precision, lending itself well to aerospace applications and high volume production runs of precision components.

Filing



A file is an abrasive surface like this one that allows machinists to remove small, imprecise amounts of metal.

Filing is combination of grinding and saw tooth cutting using a file. Prior to the development of modern machining equipment it provided a relatively accurate means for the production of small parts, especially those with flat surfaces. The skilled use of a file allowed a machinist to work to fine tolerances and was the hallmark of the craft. Today filing is rarely used as a production technique in industry, though it remains as a common method of deburring.

Other

Broaching is a machining operation used to cut keyways into shafts. Electron beam machining (EBM) is a machining process where high-velocity electrons are directed toward a work piece, creating heat and vaporizing the material. Ultrasonic machining uses ultrasonic vibrations to machine very hard or brittle materials.

Joining processes



Mig welding

Welding

Welding is a fabrication process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the workpieces and adding a filler material to form a pool of molten material that cools to become a strong joint, but sometimes pressure is used in conjunction with heat, or by itself, to produce the weld.

Many different energy sources can be used for welding, including a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound. While often an industrial process,

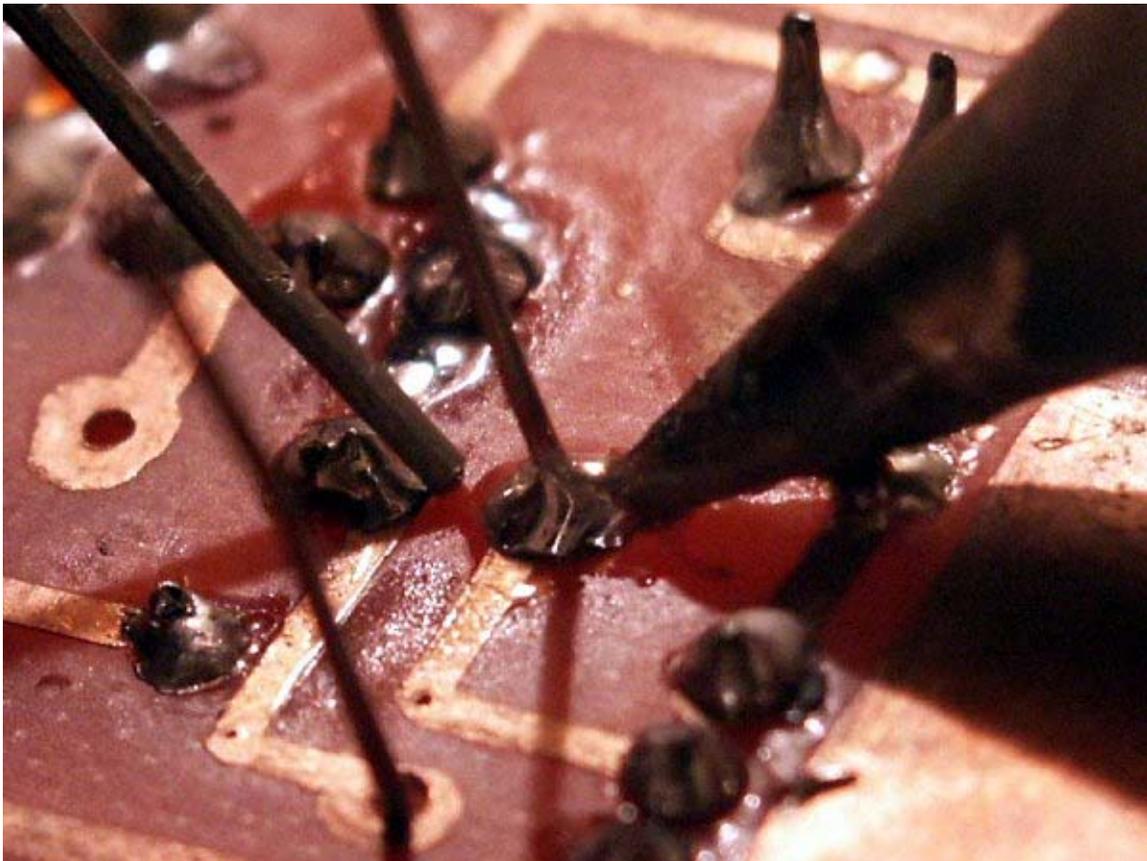
welding can be done in many different environments, including open air, underwater and in space. Regardless of location, however, welding remains dangerous, and precautions must be taken to avoid burns, electric shock, poisonous fumes, and overexposure to ultraviolet light.

Brazing

Brazing is a joining process in which a filler metal is melted and drawn into a capillary formed by the assembly of two or more work pieces. The filler metal reacts metallurgically with the workpiece(s) and solidifies in the capillary, forming a strong joint. Unlike welding, the work piece is not melted. Brazing is similar to soldering, but occurs at temperatures in excess of 450 °C (842 °F). Brazing has the advantage of producing less thermal stresses than welding, and brazed assemblies tend to be more ductile than weldments because alloying elements can not segregate and precipitate.

Brazing techniques include, flame brazing, resistance brazing, furnace brazing, diffusion brazing, and inductive brazing.

Soldering



Soldering a printed circuit board.

Soldering is a joining process that occurs at temperatures below 450 °C (842 °F). It is similar to brazing in the fact that a filler is melted and drawn into a capillary to form a joint, although at a lower temperature. Because of this lower temperature and different alloys used as fillers, the metallurgical reaction between filler and work piece is minimal, resulting in a weaker joint.

Riveting

Riveting is one of the most ancient metalwork joining processes. Its use has declined markedly during the second half of the 20th century, but it still retains important uses in industry and construction into the 21st century. The earlier use of rivets is being superseded by improvements in welding and component fabrication techniques.

A rivet is essentially a two-headed and unthreaded bolt which holds two other pieces of metal together. Holes are drilled or punched through the two pieces of metal to be joined. The holes being aligned, a rivet is passed through the holes and permanent heads are formed onto the ends of the rivet utilizing hammers and forming dies (by either coldworking or hotworking). Rivets are commonly purchased with one head already formed.

When it is necessary to remove rivets, one of the rivet's heads is sheared off with a cold chisel. The rivet is then driven out with a hammer and punch.

Associated processes

While these processes are not primary metalworking processes, they are often performed before or after metalworking processes.

Heat treatment

Metals can be heat treated to alter the properties of strength, ductility, toughness, hardness or resistance to corrosion. Common heat treatment processes include annealing, precipitation strengthening, quenching, and tempering. The **annealing** process softens the metal by allowing recovery of cold work and grain growth. **Quenching** can be used to harden alloy steels, or in precipitation hardenable alloys, to trap dissolved solute atoms in solution. **Tempering** will cause the dissolved alloying elements to precipitate, or in the case of quenched steels, improve impact strength and ductile properties.

Often, mechanical and thermal treatments are combined in what is known as thermo-mechanical treatments for better properties and more efficient processing of materials. These processes are common to high alloy special steels, super alloys and titanium alloys.

Plating

Electroplating is a common surface-treatment technique. It involves bonding a thin layer of another metal such as gold, silver, chromium or zinc to the surface of the product. It is used to reduce corrosion as well as to improve the product's aesthetic appearance.

Thermal spraying

Thermal spraying techniques are another popular finishing option, and often have better high temperature properties than electroplated coatings.

Chapter-2

Foundry



Glow of a foundry crucible

A **foundry** is a factory that produces metal castings. Metals are cast into shapes by melting them into a liquid, pouring the metal in a mold, and removing the mold material or casting after the metal has solidified as it cools. The most common metals processed are aluminum and cast iron. However, other metals, such as bronze, steel, magnesium, copper, tin, and zinc, are also used to produce castings in foundries.

Process

Melting

Melting is performed in a furnace. Virgin material, external scrap, internal scrap, and alloying elements are used to charge the furnace. Virgin material refers to commercially pure forms of the primary metal used to form a particular alloy. Alloying elements are either pure forms of an alloying element, like electrolytic nickel, or alloys of limited composition, such as ferrous alloys or master alloys. External scrap is material from other forming processes such as punching, forging, or machining. Internal scrap consists of the gates, risers, or defective castings.

The process includes melting the charge, refining the melt, adjusting the melt chemistry and tapping into a transport vessel. Refining is done to remove deleterious gases and elements from the molten metal to avoid casting defects. Material is added during the melting process to bring the final chemistry within a specific range specified by industry and/or internal standards. During the tap, final chemistry adjustments are made.

Furnace

Several specialised furnaces are used to melt the metal. Furnaces are refractory lined vessels that contain the material to be melted and provide the energy to melt it. Modern furnace types include electric arc furnaces (EAF), induction furnaces, cupolas, reverberatory, and crucible furnaces. Furnace choice is dependent on the alloy system and quantities produced. For ferrous materials, EAFs, cupolas, and induction furnaces are commonly used. Reverberatory and crucible furnaces are common for producing aluminum castings.

Furnace design is a complex process, and the design can be optimized based on multiple factors. Furnaces in foundries can be any size, ranging from mere ounces to hundreds of tons, and they are designed according to the type of metals that are to be melted. Also, furnaces must be designed around the fuel being used to produce the desired temperature. For low temperature melting point alloys, such as zinc or tin, melting furnaces may reach around 327 Celsius. Electricity, propane, or natural gas are usually used for these temperatures. For high melting point alloys such as steel or nickel based alloys, the furnace must be designed for temperatures over 3600 Celsius. The fuel used to reach these high temperatures can be electricity or coke.

The majority of foundries specialize in a particular metal and have furnaces dedicated to these metals. For example, an iron foundry (for cast iron) may use a cupola, induction furnace, or EAF, while a steel foundry will use an EAF or induction furnace. Bronze or brass foundries use crucible furnaces or induction furnaces. Most aluminum foundries use either an electric resistance or gas heated crucible furnaces or reverberatory furnaces.

Degassing

In the case of aluminium alloys, a degassing step is usually necessary to reduce the amount of hydrogen in the liquid metal. If the hydrogen concentration in the melt is too high, the resulting casting will contain gas porosity that will deteriorate its mechanical properties.

An efficient way of removing hydrogen from the melt is to bubble argon or nitrogen. To do that, several different types of equipment are used by foundries. When the bubbles go up in the melt, they catch the dissolved hydrogen and bring it to the top surface. There are various equipment which measure the amount of hydrogen present in it. Alternatively, the density of the aluminum sample is calculated to check amount of hydrogen dissolved in it.

Mould making



Many large foundries operate their own industrial railways

In the casting process a pattern is made in the shape of the desired part. This pattern is made out of wax, wood, plastic or metal. Simple designs can be made in a single piece or solid pattern. More complex designs are made in two parts, called split patterns. A split pattern has a top or upper section, called a cope, and a bottom or lower section called a drag. Both solid and split patterns can have cores inserted to complete the final part shape. Where the cope and drag separates is called the parting line.

UNDERCUT



A diagram of an undercut in a mould.

DRAFT

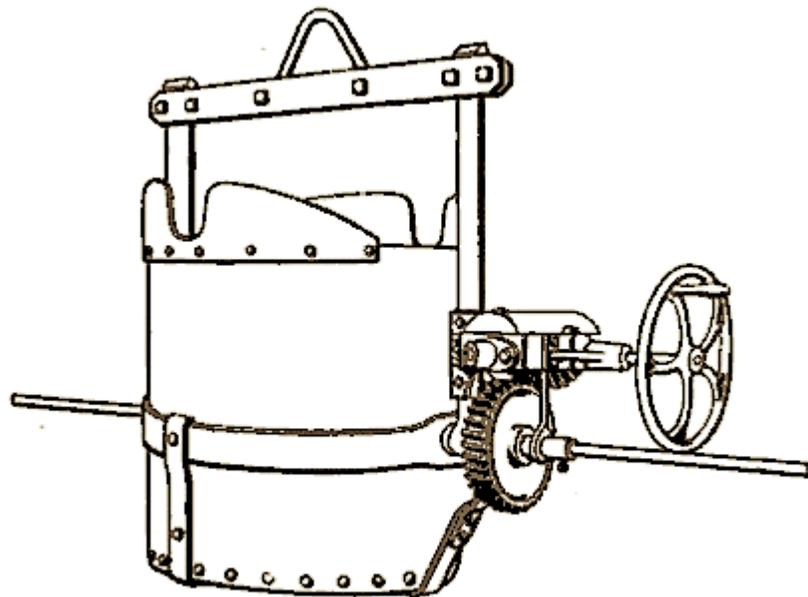


A diagram of draft on a pattern.

When making a pattern it is best to taper the edges so that the pattern can be removed without breaking the mold. This is called draft. The opposite of draft is an undercut where there is part of the pattern under the sand making it impossible to remove the pattern without damaging the mould. The molds are constructed by several different processes dependent upon the type of foundry, metal to be poured, quantity of parts to be produced, size of the casting and complexity of the casting. These mold processes include:

- Sand casting - Green or resin bonded sand mold.
- Lost-foam casting - Polystyrene pattern with a mixture of ceramic and sand mold.
- Investment casting - Wax or similar sacrificial pattern with a ceramic mold.
- Plaster casting - Plaster mold.
- V-Process casting - Vacuum is used in conjunction with thermoformed plastic to form sand molds. No moisture, clay or resin is needed for sand to retain shape.
- Billet (ingot) casting - Simple mold for producing ingots of metal normally for use in other foundries.

Pouring



Geared Ladle.

An old geared ladle

In a foundry, molten metal is poured into molds. Pouring can be accomplished with gravity, or it may be assisted with a vacuum or pressurized gas. Many modern foundries use robots or automatic pouring machines for pouring molten metal. Traditionally, molds were poured by hand using ladles.

Shakeout

The solidified metal component is then removed from its mold. Where the mold is sand based, this can be done by shaking or tumbling. This frees the casting from the sand, which is still attached to the metal runners and gates - which are the channels through which the molten metal traveled to reach the component itself.

Degating

Degating is the removal of the heads, runners, gates, and risers from the casting. Runners, gates, and risers may be removed using cutting torches, bandsaws or ceramic cutoff blades. For some metal types, and with some gating system designs, the sprue, runners and gates can be removed by breaking them away from the casting with a hammer or specially designed knockout machinery. Risers must usually be removed using a cutting method but some newer methods of riser removal use knockout machinery with special designs incorporated into the riser neck geometry that allow the riser to break off at the right place.

The gating system required to produce castings in a mold yields leftover metal, including heads, risers and sprue, sometimes collectively called sprue, that can exceed 50% of the metal required to pour a full mold. Since this metal must be remelted as salvage, the yield of a particular gating configuration becomes an important economic consideration when designing various gating schemes, to minimize the cost of excess sprue, and thus melting costs.

Surface cleaning

After degating, sand or other molding media may adhere to the casting. To remove this the surface is cleaned using a blasting process. This means a granular media will be propelled against the surface of the casting to mechanically knock away the adhering sand. The media may be blown with compressed air, or may be hurled using a shot wheel. The media strikes the casting surface at high velocity to dislodge the molding media (for example, sand, slag) from the casting surface. Numerous materials may be used as media, including steel, iron, other metal alloys, aluminum oxides, glass beads, walnut shells, baking powder among others. The blasting media is selected to develop the color and reflectance of the cast surface. Terms used to describe this process include cleaning, bead blasting, and sand blasting. Shot peening may be used to further work-harden and finish the surface.

Finishing

The final step in the process usually involves grinding, sanding, or machining the component in order to achieve the desired dimensional accuracies, physical shape and surface finish.

Removing the remaining gate material, called a gate stub, is usually done using a grinder or sanding. These processes are used because their material removal rates are slow enough to control the amount of material. These steps are done prior to any final machining.

After grinding, any surfaces that require tight dimensional control are machined. Many castings are machined in CNC milling centers. The reason for this is that these processes have better dimensional capability and repeatability than many casting processes. However, it is not uncommon today for many components to be used without machining.

A few foundries provide other services before shipping components to their customers. Painting components to prevent corrosion and improve visual appeal is common. Some foundries will assemble their castings into complete machines or sub-assemblies. Other foundries weld multiple castings or wrought metals together to form a finished product.

More and more the process of finishing a casting is being achieved using robotic machines which eliminate the need for a human to physically grind or break parting lines, gating material or feeders. The introduction of these machines has reduced injury to workers, costs of consumables whilst also reducing the time necessary to finish a casting.

It also eliminates the problem of human error so as to increase repeatability in the quality of grinding. With a change of tooling these machines can finish a wide variety of materials including iron, bronze and aluminium.

Chapter-3

Polishing and Planing (shaping)

Polishing

Polishing and **buffing** are finishing processes for smoothing a workpiece's surface using an abrasive and a work wheel. Technically *polishing* refers to processes that use an abrasive that is glued to the work wheel, while *buffing* uses a loose abrasive applied to the work wheel. Polishing is a more aggressive process while buffing is less harsh, which leads to a smoother, brighter finish. A common misconception is that a polished surface has a mirror bright finish, however most mirror bright finishes are actually buffed.

Polishing is often used to enhance the looks of an item, prevent contamination of medical instruments, remove oxidation, create a reflective surface, or prevent corrosion in pipes. In metallography and metallurgy, polishing is used to create a flat, defect-free surface for examination of a metal's microstructure under a microscope. Silicon-based polishing pads or a diamond solution can be used in the polishing process.

The removal of oxidization (tarnish) from metal objects is accomplished using a metal polish or tarnish remover; this is also called polishing. To prevent further unwanted oxidization, polished metal surfaces may be coated with wax, oil, or lacquer. This is of particular concern for copper alloy products such as brass and bronze.

Process

Polishing is usually a multistage process. The first stage starts with a rough abrasive and each subsequent stage uses a finer abrasive until the desired finish is achieved. The rough pass removes surface defects like pits, nicks, lines and scratches. The finer abrasives leave very thin lines that are not visible to the naked eye. Lubricants like wax and kerosene may be used as lubricating and cooling media during these operations, although some polishing materials are specifically designed to be used "dry." Buffing may be done by hand with a stationary polisher or die grinder, or it may be automated using specialized equipment.

When buffing there are two types of buffing motions: the *cut motion* and the *color motion*. The cut motion is designed to give a uniform, smooth, semi-bright surface finish. This is achieved by moving the workpiece against the rotation of the buffing wheel, while using medium to hard pressure. The color motion gives a clean, bright, shiny surface finish. This is achieved by moving the workpiece with the rotation of the buffing wheel, while using medium to light pressure.

When polishing brass, there are often minute marks in the metal caused by impurities. To overcome this, the surface is polished with a very fine (600) grit, copper plated, then buffed to a mirror finish with an airflow mop.

Polishing operations for items such as chisels, hammers, screwdrivers, wrenches, etc., are given a fine finish but not plated. In order to achieve this finish four operations are required: roughing, dry fining, greasing, and coloring. Note that roughing is usually done on a solid grinding wheel and for an extra fine polish the greasing operation may be broken up into two operations: rough greasing and fine greasing. However, for inexpensive items money is saved by only performing the first two operations.

Polishing knives and cutlery is known as fine glazing or blue glazing. Sand buffing, when used on German silver, white metal, etc., is technically a buffing operation because it uses a loose abrasive, but removes a significant amount of material, like polishing.

Equipment

Aluminium oxide abrasives are used on high tensile strength metals, such as carbon and alloy steel, tough iron, and nonferrous alloys. Silicon carbide abrasives are used on hard and brittle substances, such as grey iron and cemented carbide, and low tensile strength metals, such as brass, aluminium, and copper.

Polishing wheels come in a wide variety of types to fulfill a wide range of needs. The most common materials used for polishing wheels are wood, leather, canvas, cotton cloth, plastic, felt, paper, sheepskin, impregnated rubber, canvas composition, and wool; leather and canvas are the most common. Wooden wheels have emery or other abrasives glued onto them and are used to polish flat surfaces and maintained good edges. There are many types of cloth wheels. Cloth wheels that are cemented together are very hard and used for rough work, whereas other cloth wheels that are sewn and glued together are not as aggressive. There are cloth wheels that are not glued or cemented, instead these are sewed and have metal side plates for support. Solid felt wheels are popular for fine finishes. Hard roughing wheels can be made by cementing together strawboard paper disks. Softer paper wheels are made from felt paper. Most wheels are run at approximately 7500 surface feet per minute (SFM), however muslin, felt and leather wheels are usually run at 4000 SFM.

Buffing wheels, also known as mops, are either made from cotton or wool cloth and come bleached or unbleached. Specific types include: sisal, spiral sewn, loose cotton, canton flannel, domet flannel, denim, treated spiral sewn, cushion, treated vented,

untreated vented, string buff, finger buff, sisal rope, mushroom, facer, tampered, scrubbing mushroom, hourglass buff, rag, "B", climax, swansdown, airflow, coolair, and bullet.

The following chart will help in deciding which wheels and compounds to use when polishing different materials. This chart is a starting point and experienced polishers may vary the materials used to suit different applications.

Common buffing compound and wheel combinations															
	Silver, gold & thin plates			Nickel & chrome plating			Copper, brass, aluminium, pot metal & soft metals			Steel & iron			Stainless steel		
Buff type	Rough	Initial buff	Final buff	Rough	Initial buff	Final buff	Rough	Initial buff	Final buff	Rough	Initial buff	Final buff	Rough	Initial buff	Final buff
Sisal							X			X			X		
Spiral sewn					X			X			X			X	
Loose									X			X			X
Canton flannel			X			X									
String															
Compound															
Black							X			X			X		
Brown								X							
White					X				X		X				
Blue			X			X						X			
Green														X	X
Red			X			X						X			

BLACK = Emery Compound, a coarse abrasive material for removal of scratches, pits, paint, rust etc.

BROWN = Tripoli compound used for general purpose cut and color on most soft metals.

WHITE = Blizzard compound, used for color and final finish of harder metals, has a cutting action.

RED = Jeweller's Rouge, designed to polish without any cutting action. Safe on thin plates. Use on its own wheel.

BLUE = A dryer, almost greaseless wheel - designed to polish without any cutting action. Safe on thin plates. Use on its own wheel.

GREEN = Used exclusively for Stainless Steel.

Applications

Polishing may be used to enhance the looks of certain parts on cars, motorbikes, handrails, cookware, kitchenware, and architectural metal applications. Pharmaceutical, dairy, and water pipes are buffed to maintain hygienic conditions and prevent corrosion. Buffing is used to manufacture of high-quality lighting reflectors.

Planing (shaping)

Planing is a manufacturing process of material removal in which the workpiece reciprocates against a stationary single-point cutting tool producing a plane or sculpted surface. Planing is analogous to shaping. The main difference between these two processes is that in shaping the tool reciprocates across the stationary workpiece. Planing motion is the opposite of shaping. Both planing and shaping are rapidly being replaced by milling.

The mechanism used for this process is known as a planer. The size of the planer is determined by the largest workpiece that can be machined on it. The cutting tools are usually carbide tipped or made of high speed steel and resemble those used in facing and turning.

Process Characteristics

- Uses single-point cutting tools
- Involves a reciprocating motion between the tool and workpiece
- Produces plane or sculpted surfaces
- Leaves parallel feed marks

Process

In shaping, the tool is brought into position with the workpiece. The tool then repeatedly moves in a straight line while the workpiece is incrementally fed into the line of motion of the tool, this produces a flat, smooth, and sculpted surface. For shaped pieces the tool reciprocates across the stationary workpiece. The tools are usually tilted or lifted after each stroke. This is done hydraulically or manually in order to prevent the tool surface from chipping when the workpiece travels back across.

Workpiece Geometry

Planing can be used to produce flat surfaces, as well as cross-sections with grooves and notches, are produced along the length of workpiece. Shaping is basically the same as planing, except the workpiece is usually smaller, and it is the tool that moves and not the workpiece. Planing can be used to produce horizontal, vertical, or inclined flat surfaces on workpieces usually too large for shaping. Shaping is used not only for flat surfaces, but also for external or internal surfaces (either horizontal or inclined). Curved and irregular surfaces can also be produced by using special attachments

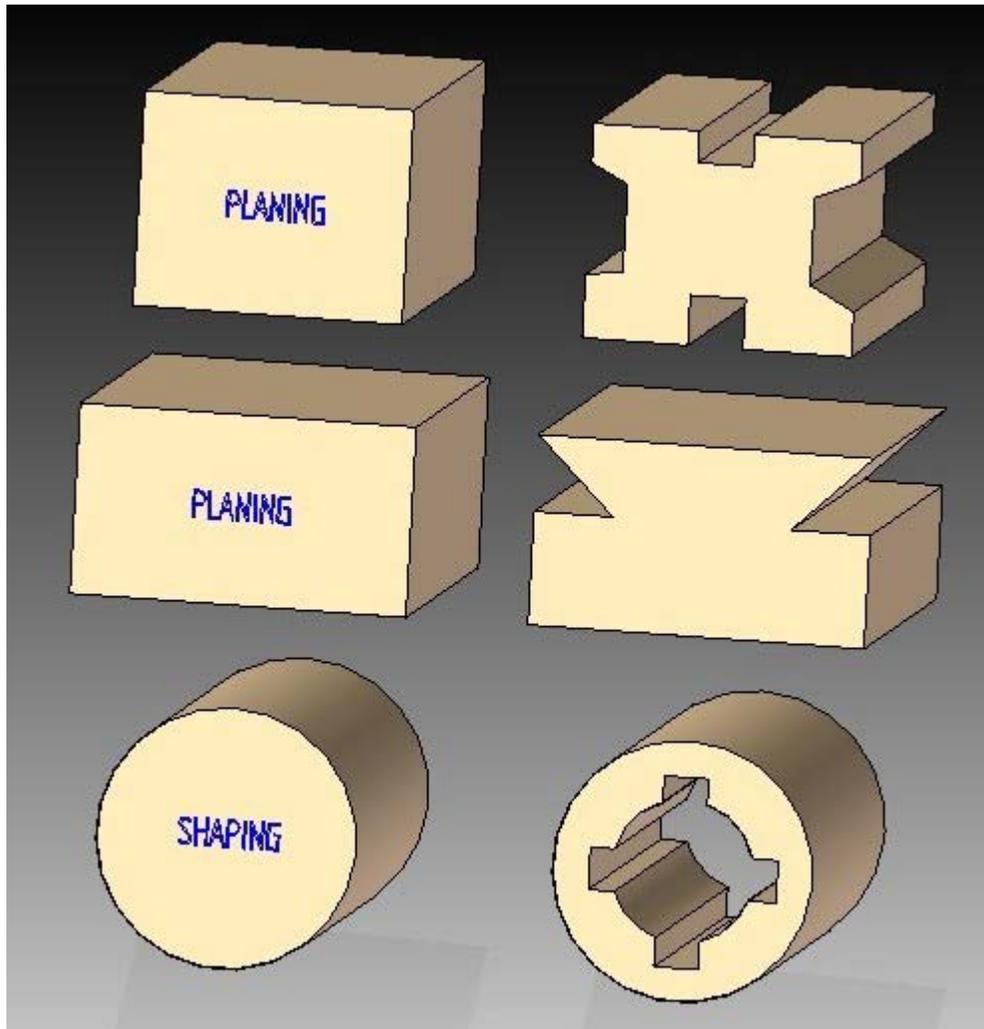
Setup and Equipment

Flat, angular, and contoured surfaces are made by horizontal shapers. Concerning shaping, the device that holds the piece being worked on has a very heavy movable jaw to withstand cutting forces. The size of the planer needed is determined by the workpiece.

Depending on the size of the workpiece many clamps and supporting devices may be used to hold it on the planer.

Typical Tools and Geometry Produced

The tools for shaping/planing are usually made of high speed steel or carbide tipped. Except for some slight angle difference, cutting tools resemble those used in facing and turning. Some advantages of using single-point cutting tools over multipoint tools is that they are more easily sharpened and fabricated. Internal shapes can be made by using a special extension tool.



Before and after geometry

Material Properties

Although the most common material to be planed or shaped is wood, there are planers and shaping machines capable of processing anything from metal pieces to plastic objects.

Chapter-4

Parts Cleaning

Parts cleaning is essential to many industrial processes, as a prelude to surface finishing or to protect sensitive components. Electroplating is particularly sensitive to part cleanliness, since molecular layers of oil can prevent adhesion of the coating. ASTM B322 is a standard guide for cleaning metals prior to electroplating. Cleaning processes include solvent cleaning, hot alkaline detergent cleaning, electrocleaning, and acid etch. The most common industrial test for cleanliness is the waterbreak test, in which the surface is thoroughly rinsed and held vertical. Hydrophobic contaminants such as oils cause the water to bead and break up, allowing the water to drain rapidly. Perfectly clean metal surfaces are hydrophilic and will retain an unbroken sheet of water that does not bead up or drain off. ASTM F22 describes a version of this test. This test does not detect hydrophilic contaminants, but the electroplating process can displace these easily since the solutions are water-based. Surfactants such as soap reduce the sensitivity of the test, so these must be thoroughly rinsed off.

Definitions and classifications

For the activities described here the following terms are often found: metal cleaning, metal surface cleaning, component cleaning, degreasing, parts washing, parts cleaning. These are well established in technical language usage but they have their shortcomings. Metal cleaning can easily be mixed up with refinement of unpurified metals. Metal surface cleaning and metal cleaning do not consider the increasing usage of plastics and composite materials in this sector. The term component cleaning leaves out the cleaning of steel sections and sheets and finally degreasing only describes a part of the topic as in most cases also chips, fines, particles, salts etc. have to be removed.

The terms 'commercial and industrial parts cleaning', 'parts cleaning in craft and industry' or 'commercial parts cleaning' probably best describe this field of activity. There are some specialists who prefer the term 'industrial parts cleaning', because they want to exclude maintenance of buildings, rooms, areas, windows, floors, tanks, machinery, hygiene, hands washing, showers etc.

Elements and their interactions



Factors

Cleaning activities in this sector can only be characterised sufficiently by a description of a number of different factors. These are outlined in illustration 1.

Parts and materials to be cleaned

First, consider the parts to be cleaned. They may consist of non- or hardly-processed sections, sheets and wires. But also machined parts or assembled components needing cleaning. Therefore, they may be composed of different metals or different combinations of metals. Plastics and composite materials can frequently be found and indeed are on the increase because e.g. the automobile industry as well as others uses more and more lighter materials.

Mass and size can be very important for the selection of cleaning methods, for example big shafts for ships are usually cleaned manually, whereas tiny shafts for electrical appliances are often cleaned in bulk in highly automated plants.

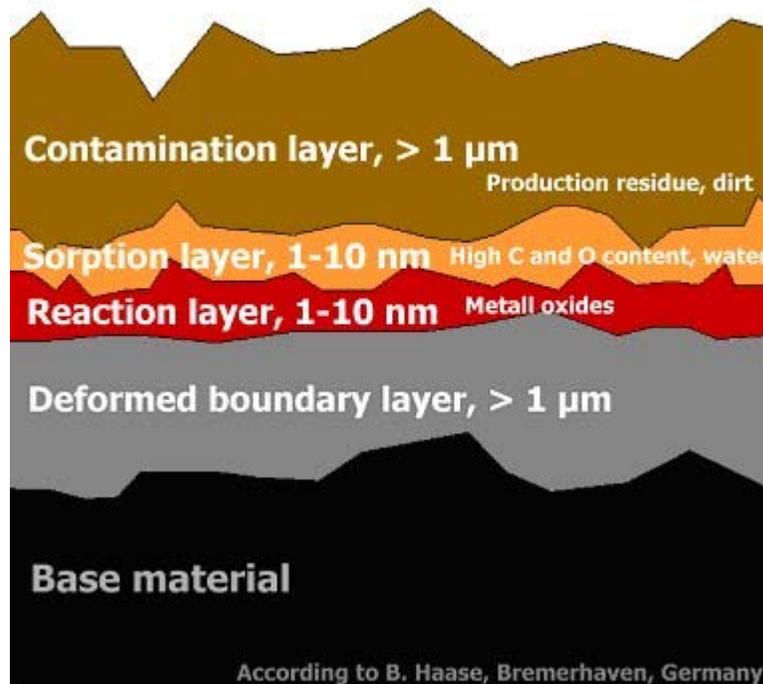
Similarly important is the geometry of the parts. Long, thin, branching, threaded holes, which could contain jammed chips, feature among the greatest challenges in this technical field. High pressure and the power wash process are one way to remove these chips as well as robots, which are programmed to exactly flush the drilled holes under high pressure.

Contaminations

The parts are usually covered by unwanted substances, the contaminations or soiling. The definition used is quite varied. In certain cases these coverings may be desired: e.g. one may not wish to remove a paint layer but only the material on top. In another case, where

crack proofing is necessary one has to remove the paint layer and it is regarded as an unwanted substance.

The classification of soiling follows the layer structure starting from the base material:



Structure of a metallic surface

- Deformed boundary layer, > 1 µm
- Reaction layer, 1 - 10 nm
- Sorption layer, 1 - 10 nm
- Contamination layer, > 1 µm

See illustration 2: Structure of a metallic surface

The nearer the layers are to the substrate surface, the more energy is needed to remove them. Correspondingly the cleaning itself can be structured according to the type of energy input :

- mechanical - abrasive: blasting, grinding
- mechanical - non-abrasive: stirring, mixing, ultrasound, spraying
- thermal - reactive: heat treatment much above 100°C in reactive gases
- thermal - non-reactive: temperature below 100°C, increased bath temperature, vapour degreasing
- chemical - abrasive/reactive: pickling in liquids, plasma-assisted, sputter-cleaning, elektropolishing

- chemical - non-reactive: organic solvents, aqueous solutions, supercritical CO₂

The contamination layer may then be further classified according to:

- Origin
- Composition: e.g. cooling lubricants may be composed very differently, thereby single components may account for big problems especially for job shop cleaners, who have no control over prior processes and thus don't know the contaminants. For example silicates may obstruct nitriding.
- State of aggregation
- Chemical and physical properties

The American Society for Testing and Materials (ASTM) presents six groups of contaminations in their manual "Choosing a cleaning process" and relates them to the most common cleaning methods, thereby the suitability of cleaning methods for the removal of a given contaminate is discussed in detail. In addition they list exemplary cleaning processes for different typical applications. Since one has to consider very many different aspects when choosing a process, this can only serve as a first orientation. The groups of contaminants are stated as follows:

- Pigmented drawing compounds
- Unpigmented oil and grease
- Chips and cutting fluids
- Polishing and buffing compounds
- Rust and scale
- Others

Charging

In order to select suitable equipment and media it should be known also which amount and which throughput has to be handled. Small amounts can hardly be cleaned economically in larger plants. Also the type of charging has to be ascertained. Sensitive parts sometimes need to be fixed in boxes. Very economically when dealing with large amounts is bulk charging, but it is quite difficult to achieve a sufficient level of cleanliness with flat pieces clinging together. Also drying can be difficult in these cases.

Place of cleaning

Another consideration is the place of cleaning. E.g. is the cleaning to be done on site, which can be the case with repair and maintenance work.

Usually the cleaning takes place in a workshop. Several common methods are solvent degreasing, vapor degreasing and using an aqueous parts washer. Companies often want the charging, loading and unloading to be integrated into the production line, which is much more demanding as regards size and throughput ability of the cleaning system.

Such cleaning systems often exactly match the requirements regarding parts, contaminants and charging methods (special production). Nonetheless central cleaning equipment, often built as multi task systems, are commonly used. These systems can suit different cleaning requirements. Typical examples are the wash stands or the small cleaning machines which are found in many industrial plants.

Cleaning equipment and procedure

First, one can differentiate between the following techniques:

- Manual
- Mechanical
- Automatic
- Robot supported

The process may be performed in one step, which is especially true for the manual cleaning, but typically it requires several steps. Therefore, it is not uncommon to find 10 to 20 steps in large plants e.g. for the medical and optical industry. This can be especially complex because non-cleaning steps may be integrated in such plants like application of corrosion protection layers or phosphating. Cleaning can also be simple, the cleaning processes are integrated into other processes as it is the case with electroplating or galvanising, where it usually serves as a pre-treatment step.

The following procedure is quite common:

1. Pre cleaning
2. Main cleaning
3. Rinsing
4. Rinsing with deionised water
5. Rinsing with corrosion protection
6. Drying

Each of these steps may take place in its own bath or chamber or in case of spray cleaning in its own zone (line or multi-chamber equipment). But quite often these steps may have a single chamber into which the respective media are pumped in (single chamber plant).

Besides equipment and procedure, cleaning media plays an important role as it removes the contaminants from the substrate.

For liquid media the following cleaners are in use: aqueous agents, semi-aqueous agents (an emulsion of solvents and water), hydrocarbon based solvents and halogenated solvents. Usually the latter are referred to as chlorinated agents, but there are also brominated and fluorated substances in (limited) use, that is why we have chosen the higher level classification. The hazardous traditionally used chlorinated agents TCI and

PCE are nowadays only applied in airtight plants and the modern volume shift systems limits any emissions.

Aqueous cleaners are mostly a combination of various substances like Alkaline builders, surfactants, sequestering agents, etc. Their use is on the rise as their results have proven to be in many cases as good or better than hydrocarbon cleaners. Additionally, the wastes generated are less hazardous resulting in less costly disposal. In the group of hydrocarbon based solvents, there are some newly developed agents like fatty acid esters made of natural fats and oils, modified alcohols and dibasic esters.

Aqueous cleaners have advantages as regards to particle and polar contaminants and only require higher inputs of mechanical and thermal energy to be effective, whereas solvents easily remove oils and greases but have health and environmental risks. In addition most solvents are flammable and create fire and explosion hazards. Now days, with the proper equipment, it is generally accepted that aqueous cleaners remove oil and grease as easily as solvents.

Another approach is with solid cleaning media (blasting) which constitutes of the CO₂ dry ice process: For tougher requirements pellets are used while for more sensitive materials or components CO₂ in form of snow is applied. One draw back is the high energy consumption required to make dry ice.

Last but not least there are processes without any media like vibration, laser, brushing and blow/exhaust systems.

All cleaning steps are characterised by media and applied temperatures and their individual agitation/application (mechanical impact). There is a wide range of different methods and combinations of these methods:

- Sprinkling
- Spraying
- Power Wash Process
- Blasting
- Flooding
- Movement of parts (turning, oscillating, pivoting)
- Circulation of bath
- Gas or air injection into bath
- Boiling under pressure
- Injection flooding
- Pressure flooding
- Hydroson
- Ultrasonic
- Megasonic

Finally, every cleaning step is described by the time which the parts to be cleaned spends in the respective zone, bath or chamber and thus medium, temperature and agitation can impact on the contamination.

Every cleaning equipment needs a so-called periphery. This term describes measures and equipment on the one hand side to maintain and control baths and on the other hand side to protect human beings and the environment.

In most plants the cleaning agents are circulated until their cleaning power has eventually decreased and reached the maximum tolerable contaminant level. In order to delay the necessary bath exchange as much as possible there are sophisticated treatment attachments in use, removing contaminants and the used up agents from the system. At the same time fresh cleaning agents or parts thereof have to be supplemented, which requires a bath control. The latter is more and more facilitated online and thus allows a computer aided adjustment of the bath. With the help of oil separators, demulsifying agents and evaporators aqueous processes can be conducted 'waste water free'. Complete exchange of baths becomes only necessary every 3 to 12 months.

When using organic solvents the preferred method to achieve a long operating bath life is distillation, an especially effective method to separate contaminants and agents.

The periphery also includes measures to protect the workers like encapsulation, automatic shut off of power supply, automatic refill and sharpening of media (e.g. gas shuttle technique), explosion prevention measures, exhaust ventilation etc., and also measures to protect the environment, e.g. capturing of volatile solvents, impounding basins, extraction, treatment and disposal of resulting wastes. Solvents based cleaning processes have the advantage that the dirt and the cleaning agent can be more easily separated, whereas in aqueous processes is more complex.

In processes without cleaning media like laser ablation and vibration cleaning, only the removed dirt has to be disposed of as there is no cleaning agent. Quite little waste is generated in processes like CO₂ blasting and automatic brush cleaning at the expense of higher energy costs.

Quality requirements

A standardisation of the quality requirements for cleaned surfaces regarding the following process (e.g. coating, heat treatment) or from the point of view of technical functionality is difficult. However it is possible to use general classifications. In Germany it was attempted to define cleaning as a sub category of metal treatment (DIN 8592: Cleaning as sub category of cutting processes), but this does not cope with all the complexities of cleaning.

The rather general rules includes the classification in intermediate cleaning, final cleaning, precision cleaning and critical cleaning (s. table), in practice seen only as a general guideline.

Terms	Max. allowed dirt	Soils removed	Explanations
Intermediate cleaning			E.g. in metal cutting manufacturing
Final cleaning	$\leq 500 \text{ mg / m}^2$ (1)	Mil-sized particles and residues thicker than a monolayer	E.g. before assembling or coating
<ul style="list-style-type: none"> Parts for phosphating, painting, enamelling 	<ul style="list-style-type: none"> $500 - \leq 5 \text{ mg C / m}^2$ (2) 		
<ul style="list-style-type: none"> Parts for case-hardening, nitriding, nitrocarburising resp. vacuum treatment 	<ul style="list-style-type: none"> $500 - \leq 5 \text{ mg C / m}^2$ (2) 		
<ul style="list-style-type: none"> Parts for electroplating, electronic parts 	<ul style="list-style-type: none"> $20 - \leq 5 \text{ mg C / m}^2$ (2) 		
Precision cleaning	$\leq 50 \text{ mg / m}^2$ (1)	Supermicrometre particles and residues <i>thinner</i> than a monolayer	Controlled environment (Durkee)
Critical cleaning	$\leq 5 \text{ mg / m}^2$ (1)	Sub-micrometre particles and non-volatile residue measured in Angstroms	cleanroom (Durkee)

(1) Related to the total dirt; (2) Only related to Carbon

Thus in practice the rule of thumb is still followed, stating that the quality requirements are met, if the subsequent process does not cause any problems, for example a paint coating does not flake off before the guarantee period ends.

Where this is not sufficient, especially in case of external orders, because of missing standards there are often specific customer requirements regarding remaining contamination, corrosion protection, spots and gloss level etc.

Measuring methods to ensure quality therefore do not play a bigger role in the workshops, although there exist a broad scale of different methods, from visual control over simple testing methods (among other things water break test, wipe test, measurement of contact angle, test inks, tape test) to complex analysis methods (among others gravimetric test, particle counting, infrared spectroscopy, glow discharge spectroscopy, energy dispersive X-ray analysis, scanning electron microscopy and electrochemical methods). Nevertheless there are only few methods, which can be applied directly in the line and which offer reproducible and comparable results. It was not until recently that bigger advancements in this area have been made

The general situation has changed meanwhile, because of dramatically rising cleanliness requirements for certain components in the automotive industry. For example brake systems and fuel-injection systems need to be fitted with increasingly smaller diameters and they have to withstand increasingly higher pressures. Therefore, a very minor particle contamination may lead to big problems. Due to the rising innovation speed, the industry cannot afford to identify possible failures at a relatively late stage. Therefore, the standard VDA 19/ISO 16232 'Road Vehicles – Cleanliness of Components of Fluid Circuits' was developed which describes methods that can control the compliance with the cleanliness requirements.

Subsequent process

When choosing cleaning techniques, cleaning agents and cleaning processes, the subsequent processes, i.e. the further processing of the cleaned parts is of special interest.

The classification follows basically the metal work theory:

- machining
- cutting
- joining
- coating
- heat treatment
- assembling
- measuring, testing
- repairing, maintenance.

In the course of time empirical values were established, how efficient the cleaning has to be, to assure the processes for the particular guarantee period and beyond. Choosing the cleaning method often starts from here.

Challenges and trends

The details above illustrate how extremely complex this specific field is. Already small changes in the requirements can necessitate completely different processes. Thus it defies scientific technical determination. On the other hand it becomes more and more important to receive the required degree of cleanliness as cost-effective as possible and with continuously minimised health and environmental risks, because cleaning has become of central importance for the supply chain in manufacturing . Applying companies usually rely on their suppliers, who—due to a big experience base—suggest adequate equipment and processes, which are then adapted to the detailed requirements in tests stations at the supplier’s premises. However they are limited to their scope of technology. To put practitioners in a position to consider all relevant possibilities meeting their requirements, some institutes have developed different tools:

SAGE: Unfortunately no longer in operation the comprehensive expert system for parts cleaning and degreasing provided a graded list with relatively general processes of possible solvent and process alternatives. Developed by the Surface Cleaning Programme at the Research Triangle Institute, Raleigh, North Carolina, USA, in cooperation with the U.S. EPA.

Cleantool: A ‘Best Practice’ database in seven languages with comprehensive and specific processes, directly recorded in companies. It contains furthermore an integrated evaluation tool, which covers the areas technology, quality, health and safety at work, environmental protection as well as costs. Also included is a comprehensive glossary.

Bauteilreinigung: A selection system for component cleaning developed by the University of Dortmund, assisting the users to analyse their cleaning tasks with regard to the suitable cleaning processes and cleaning agents.

TURI, Toxic Use Reduction Institute: A department of the University of Lowell, Massachusetts (USA). TURI's laboratory has been conducting evaluations on alternative cleaning products since 1993. A majority of these products were designed for metal surface cleaning. The results of these tests are available on-line through the Institute’s laboratory database.

Chapter-5

Hot Working and Hot Pressing

Hot working



A forge fire for hot working of metal

Hot working refers to processes where metals are plastically deformed above their recrystallization temperature. Being above the recrystallization temperature allows the material to recrystallize during deformation. This is important because recrystallization keeps the materials from strain hardening, which ultimately keeps the yield strength and hardness low and ductility high. This contrasts with cold working.

Temperature

The lower limit of the hot working temperature is determined by its recrystallization temperature. As a guideline, the lower limit of the hot working temperature of a material is 0.6 times its melting temperature (on an absolute temperature scale). The upper limit for hot working is determined by various factors, such as: excessive oxidation, grain growth, or an undesirable phase transformation. In practice materials are usually heated to the upper limit first to keep forming forces as low as possible and to maximize the amount of time available to hot work the workpiece.

The most important aspect of any hot working process is controlling the temperature of the workpiece. Of 90% of the energy imparted into the workpiece is converted into heat. Therefore, if the deformation process is quick enough the temperature of the workpiece should rise, however, this does not usually happen in practice. Most of the heat is lost through the surface of the workpiece into the cooler tooling. This causes temperature gradients in the workpiece, usually due to non-uniform cross-sections where the thinner sections are cooler than the thicker sections. Ultimately, this can lead to cracking in the cooler, less ductile surfaces. One way to minimize the problem is to heat the tooling. The hotter the tooling the less heat lost to it, but as the tooling temperature rises, the tool life decreases. Therefore the tooling temperature must be compromised; commonly, hot working tooling is heated to 500–850 °F (325–450 °C).

Metal	Temperature
Tin	Room temperature
Steel	2,000 °F (1,090 °C)
Tungsten	4,000 °F (2,200 °C)

Advantages & disadvantages

The advantages are:

- Decrease in yield strength, therefore it is easier to work and uses less energy or force
- Increase in ductility
- Elevated temperatures increase diffusion which can remove or reduce chemical inhomogeneities
- Pores may reduce in size or close completely during deformation
- In steel, the weak, ductile, face-centered-cubic austenite microstructure is deformed instead of the strong body-centered-cubic ferrite microstructure found at lower temperatures

Usually the initial workpiece that is hot worked was originally cast. The microstructure of cast items does not optimize the engineering properties, from a microstructure standpoint.

Hot working improves the engineering properties of the workpiece because it replaces the microstructure with one that has fine spherical shaped grains. These grains increase the strength, ductility, and toughness of the material.

The engineering properties can also be improved by reorienting the inclusions (impurities). In the cast state the inclusions are randomly oriented, which, when intersecting the surface, can be a propagation point for cracks. When the material is hot worked the inclusions tend to flow with the contour of the surface, creating *stringers*. As a whole the strings create a *flow structure*, where the properties are anisotropic (different based on direction). With the stringers oriented parallel to the surface it strengthens the workpiece, especially with respect to fracturing. The stringers act as "crack-arrestors" because the crack will want to propagate through the stringer and not along it.

The disadvantages are:

- Undesirable reactions between the metal and the surrounding atmosphere (scaling or rapid oxidation of the workpiece)
- Less precise tolerances due to thermal contraction and warping from uneven cooling
- Grain structure may vary throughout the metal for various reasons
- Requires a heating unit of some kind such as a gas or diesel furnace or an induction heater, which can be very expensive

Hot pressing

Hot pressing is a high-pressure, low-strain-rate powder metallurgy process for forming of a powder or powder compact at a temperature high enough to induce sintering and creep processes. This is achieved by the simultaneous application of heat and pressure.

Hot pressing is mainly used to fabricate hard and brittle materials. One large use is in the consolidation of diamond-metal composite cutting tools and technical ceramics. The densification works through particle rearrangement and plastic flow at the particle contacts. The loose powder or the pre-compacted part is in most of the cases filled to a graphite mould that allows induction or resistance heating up to temperatures of typically 2,400 °C (4,350 °F). Pressures of up to 50 MPa (7,300 psi) can be applied.

Within hot pressing technology, three distinctly different types of heating can be found in use: induction heating, indirect resistance heating, and direct hot pressing.

Inductive heating

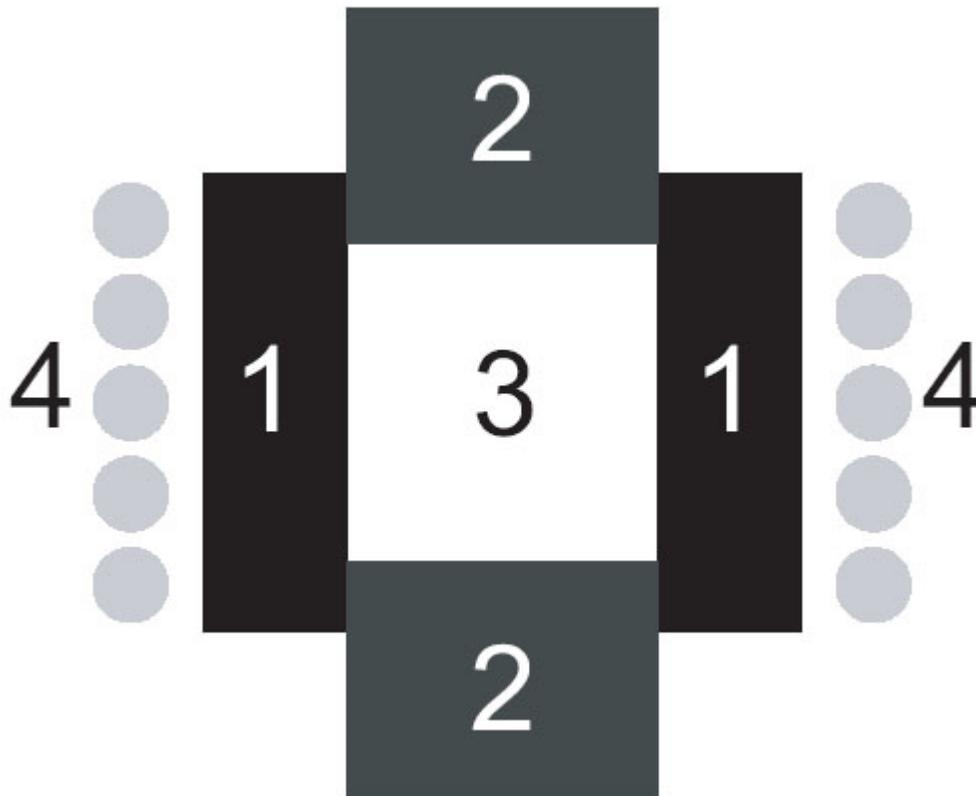


Figure I: Conventional inductive heating

In this process heat is produced within the mould when it is subjected to a high frequency electromagnetic field, generated by using an induction coil coupled to an electronic generator. The mould is made out of graphite or steel, and pressure is applied by one or two cylinders onto the punches. The mould is positioned within the induction coil. The advantage here is that the pressure and the inductive power are completely independent. Even powders with a liquid phase are amenable to this process and low pressures are possible, too. Among the disadvantages are the expense of a high-frequency generator and the need for proper alignment. If the mould is placed off centre, the heat distribution is uneven. But the main disadvantage is the dependence of the process on good inductive coupling and thermal conductivity of the mould. The magnetic field can penetrate the mould only 0.5mm to 3mm. From there on, the heat has to be "transported" into the mould by the thermal conductivity of the mould material. Uniform heating is much more difficult if the air gap between the mould and the inductive coil is not the same all along the mould profile. Another potential problem is heating rate. Too high a heat up rate will result in high temperature differences between the surface and core that can destroy the mould.

Indirect resistance heating

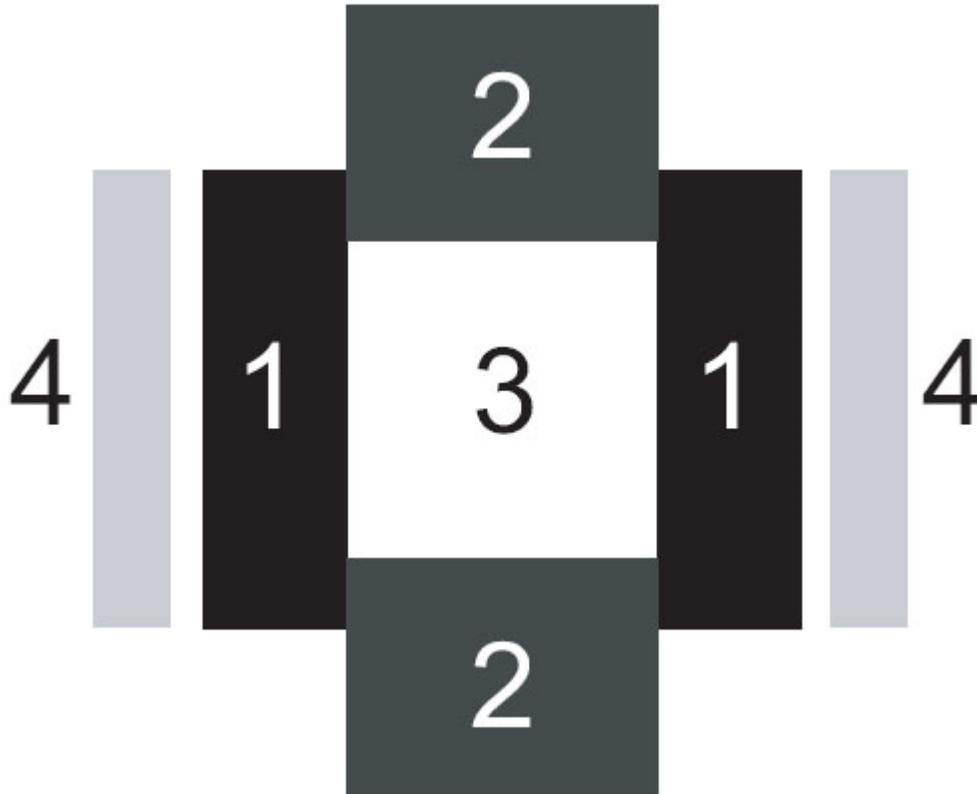


Figure II: Indirect resistance heating

With indirect resistance heating technology, the mould is placed in a heating chamber. The chamber is heated by graphite heating elements. These elements are heated by electrical current. The heat is then transferred into the mould by convection. As the electrical energy heats the heating elements that then heat the mould in a secondary manner, the process is called indirect resistance heating.

Advantages are high achievable temperatures, independent from the conductivity of the mould and independent from heat and pressure. Main disadvantage is the time that it takes to heat up the mould. It takes relatively long for heat transfer to take place from the furnace atmosphere to the mould surface and subsequently through out the cross-section of the mould.

Direct hot pressing

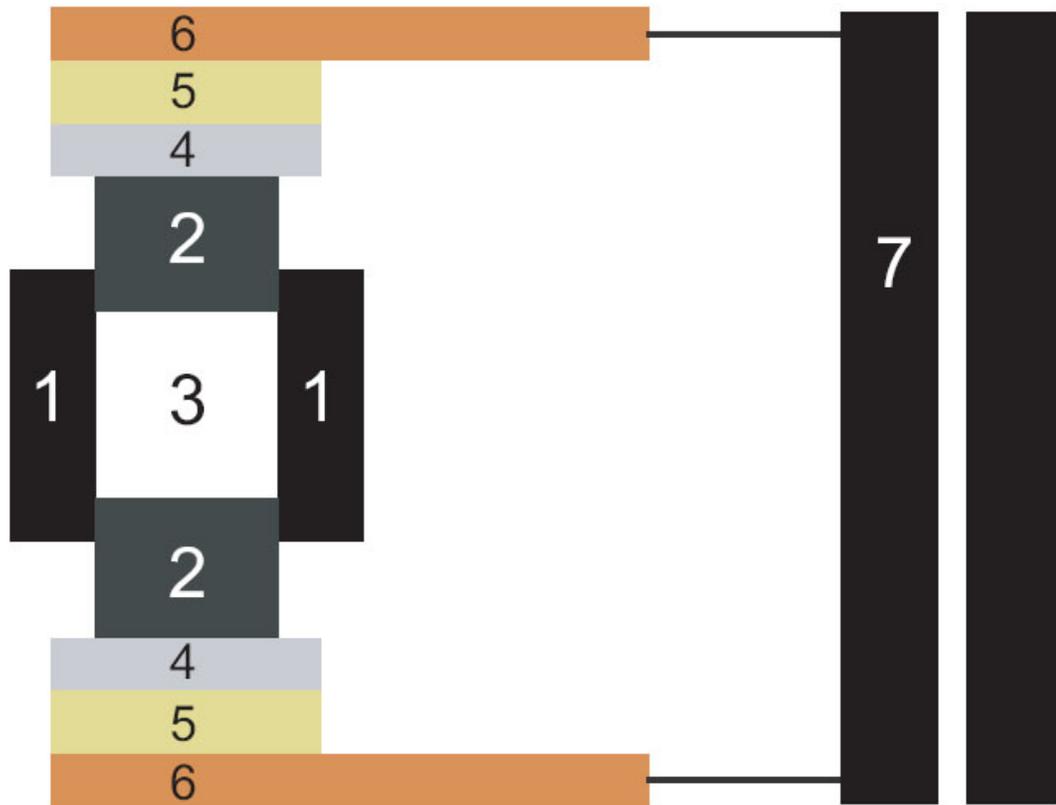


Figure III: Direct hot pressing

The basic idea of sintering with electric current going through the mould is quite old. Resistance heating of cemented carbide powders was patented by Taylor as early as 1933. This method is currently undergoing renewed interest. When applying a standard (unpulsed) AC or DC current, it is referred to as Direct Hot-Pressing (DHP) which is a common term in many industries. When applying a pulsed DC current, it is referred to as Spark Plasma Sintering (SPS) or Field Assisted Sintering Technique (FAST). The compelling reason for shortening the cycle time then was to avoid grain growth and also save energy. In direct hot pressing, the mould is directly connected to electrical power. The resistance of the mould and the powder part generates the heat directly in the mould. This results in very high heating rates. Additionally, this leads to significant increase in the sintering activity of fine metal powder aggregates which makes short cycle times of a few minutes possible. Further, this process lowers the threshold sintering temperature and pressure compared to that required in conventional sintering processes. The previous two methods are both closely dependent on the an intrinsic property of the mould material, i.e., its thermal conductivity. With direct resistance heating, however, the heat is generated where it is needed.

Recently, the manufacture of such critical items as sputtering targets and high-performance ceramic components, such as boron carbide, titanium diboride, and sialon, have been achieved. Using metal powder, the conductivity of the mould is ideal for fast heating of the work-piece. Moulds that have a big diameter and relatively small height can be heated up very fast. The process is especially suitable for applications that need high heating rates, e.g. for materials that should not be kept at high temperatures too long or for processes that require fast heating rates for high productivity.

With the direct hot pressing technology, materials can be sintered to their final density. The near net-shape precision achieved is very high and saves in many cases mechanical reworking of the high grade materials that are often difficult to process.

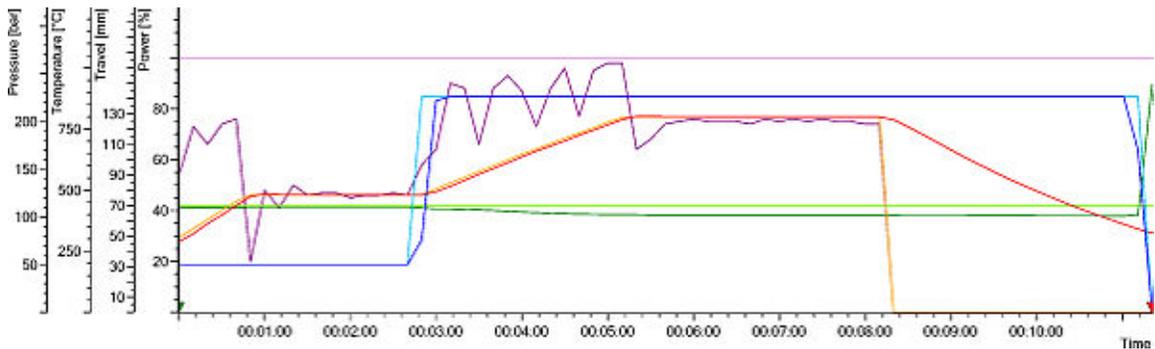


Figure IV: Process layout of the co-sintering process; total cycle time 11.5 mins Key:
 Red/orange line: actual/set temperature Green line: densification of powder/green compact Dark blue/light blue: actual/set pressure

Chapter-6

Forge



A blacksmith's coal forge



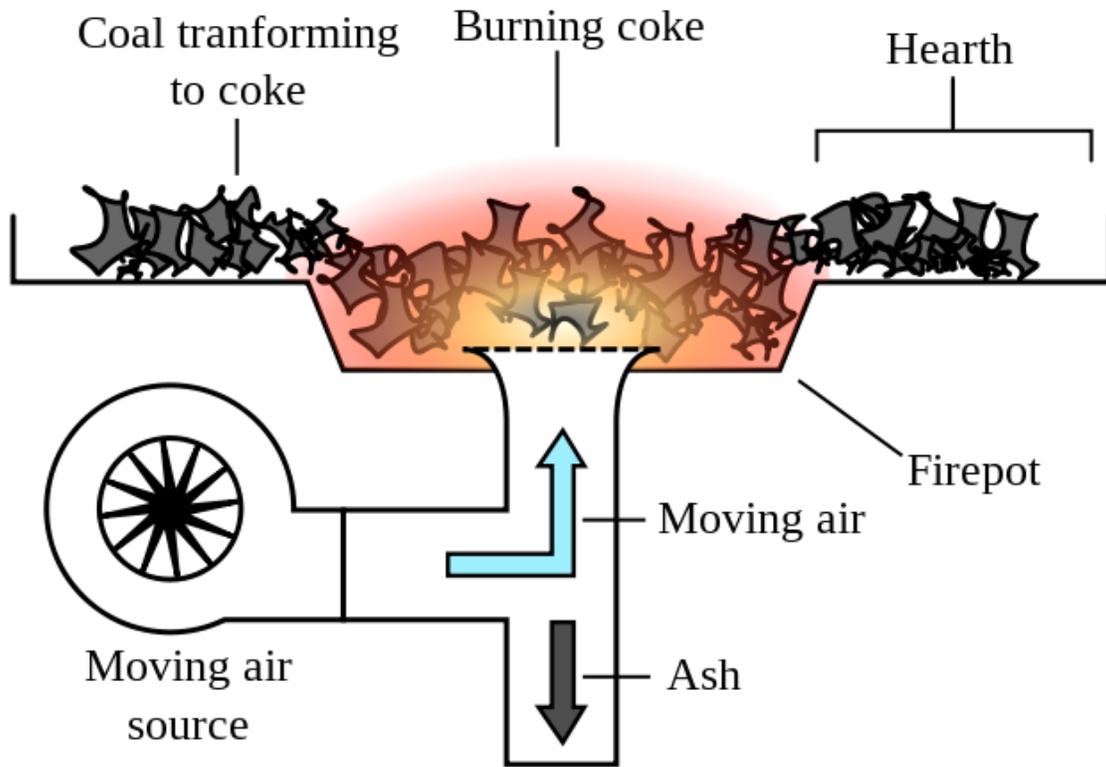
Wooden smithy in Opole, Upper Silesia

A **forge** is a hearth used for forging. The term "forge" can also refer to the workplace of a smith or a blacksmith, although the term **smithy** is then more commonly used.

The basic smithy contains a forge, also known as a hearth, for heating metals. The forge heats the workpiece to a malleable temperature (a temperature where the metal becomes easier to shape) or to the point where work hardening no longer occurs. The workpiece is transported to and from the forge using tongs. The tongs are also used to hold the workpiece on the smithy's anvil while the smith works it with a hammer. Finally the workpiece is transported to the slack tub, which rapidly cools the workpiece in a large body of water. The slack tub also provides water to control the fire in the forge.

Types of forges

Coal/coke/charcoal forge



Standard coal forge

A forge typically uses bituminous coal, industrial coke or charcoal as the fuel to heat metal. The designs of these forges have varied over time, but whether the fuel is coal, coke or charcoal the basic design has remained the same.

A forge of this type is essentially a hearth or fireplace designed to allow a fire to be controlled such that metal introduced to the fire may be brought to a malleable state or to bring about other metallurgical effects (hardening, annealing, and drawing temper as examples). The forge fire in this type of forge is controlled in three ways: amount of air, volume of fuel, and shape of the fuel/fire.



A forge fire for hot working of metal

Over thousands of years of forging, these devices have evolved in one form or another as the essential features of this type of forge:

- Tuyere — a pipe through which air can be forced into the fire
- Bellows or blower — a means for forcing air into the tuyere
- Firepot or hearth — a place where the burning fuel can be contained over or against the tuyere opening.

During operation, fuel is placed in or on the hearth and ignited. A source of moving air, such as a fan or bellows, introduces additional air into the fire through the tuyere. With additional air, the fire consumes more fuel and burns hotter.



A typical Scottish smithy at Auchentiber, North Ayrshire, Scotland.

A blacksmith balances the fuel and air in the fire to suit particular kinds of work. Often this involves adjusting and maintaining the shape of the fire.

In a typical, but by no means universal, coal forge, a firepot will be centered in a flat hearth. The tuyere will enter the firepot at the bottom. In operation, the hot core of the fire will be a ball of burning coke in and above the firepot. The heart of the fire will be surrounded by a layer of hot but not burning coke. Around the unburnt coke will be a transitional layer of coal being transformed into coke by the heat of the fire. Surrounding all is a ring or horseshoe-shaped layer of raw coal, usually kept damp and tightly packed to maintain the shape of the fire's heart and to keep the coal from burning directly so that it "cooks" into coke first.

If a larger fire is necessary, the smith increases the air flowing into the fire as well as feeding and deepening the coke heart. The smith can also adjust the length and width of the fire in such a forge to accommodate different shapes of work.

The major variation from the forge and fire just described is a 'back draft' where there is no fire pot, and the tuyere enters the hearth horizontally from the back wall.

Coke and charcoal may be burned in the same forges that use coal, but since there is no need to convert the raw fuel at the heart of the fire (as with coal), the fire is handled differently.

Individual smiths and specialized applications have fostered development of a variety of forges of this type, from the coal forge described above, to simpler constructions amounting to a hole in the ground with a pipe leading into it.

Gas forge

A gas forge typically uses propane or natural gas as the fuel. One common, efficient design uses a cylindrical forge chamber and a burner tube mounted at a right angle to the body. The chamber is typically lined with refractory materials, preferably a hard castable refractory ceramic. The burner mixes fuel and air which are ignited at the tip, which protrudes a short way into the chamber lining. The air pressure, and therefore heat, can be increased with a mechanical blower or by taking advantage of the Venturi effect.

Gas forges vary in size and construction, from large forges using a big burner with a blower or several atmospheric burners to forges built out of a coffee can utilizing a cheap, simple propane torch. A small forge can even be carved out of a single soft firebrick.

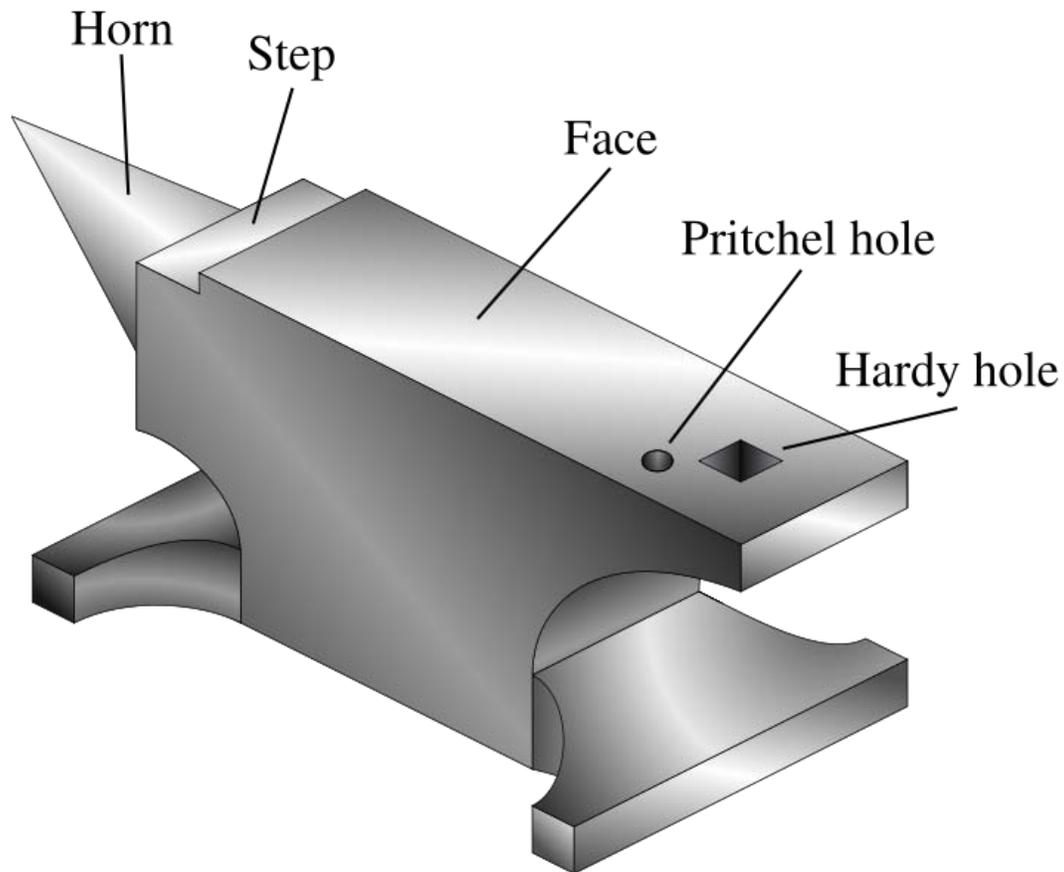
The primary advantage of a gas forge is ease of use, particularly for a novice. A gas forge is simple to operate compared to coal forges, and the fire produced is clean and consistent. They are less versatile, as the fire cannot be reshaped to accommodate large or unusually shaped pieces; It is also difficult to heat a small section of a piece. A common misconception is that gas forges cannot produce enough heat to enable forge-welding, but a well designed gas forge is hot enough for any task.

Finery forge

A finery forge is a water-powered mill where pig iron is refined into wrought iron.

Forging equipment

Anvil



The anvil serves as a work bench to the blacksmith, where the metal to be beaten is placed. Anvils are made of cast or wrought iron with a tool steel face welded on or of a single piece of cast or forged tool steel. The flat top has two holes; the wider is called the hardy hole, where the square shank of the hardy fits. The smaller hole is called the punch hole, used as clearance when punching holes in hot metal.

Chisel

Chisels are made of high carbon steel. They are hardened and tempered at the cutting edge while the head is left soft so it will not crack when hammered. Chisels are of two types, hot and cold chisels. The cold chisel is used for cutting cold metals while the hot chisel is for hot metals. Usually hot chisels are thinner and therefore can not be substituted with cold chisels.

Tongs

Tongs are used by the blacksmith for holding hot metals securely. The mouths are custom made by the smith in various shapes to suit the gripping of various shapes of metal.

Fuller

Fullers are forming tools of different shapes used in making grooves or hollows. They are often used in pairs, the bottom fuller has a square shank which fits into the hardy hole in the anvil while the top fuller has a handle. The work is placed on the bottom fuller and the top is placed on the work and struck with a hammer. The top fuller is also used for finishing round corners and for stretching or spreading metal.

Hardy

The hardy is a cutting tool similar to the chisel. It is used as a chisel or hammer for cutting both hot and cold metals. It has a square shank that fits into the hardy hole in the anvil, with the cutting edge facing upwards. The metal to be cut is placed on the cutting edge and struck with a hammer. They are also used with set tools which are placed over the workpiece and struck.

Slack tub

A *slack tub* is usually a large container full of water, brine, or oil used by a blacksmith to quench hot metal. The term is believed to derive from the word "slake", as in slaking the heat.

Types of Forging

Drop Forging

Drop forging is a process used to shape metal into complex shapes by dropping heated metal into a punch and die which compresses to gradually change the shape of the metal.

Process

The workpiece is placed into a die and punch, then the impact of a ram on the punch causes the heated material, which is very malleable, to conform to the shape of the punch and die cavities. Typically only one ram is needed to completely form the part. The extra space between the die and punch is called the flash. It acts as a relief valve for the extreme pressure produced by the closing of the die halves but is eventually trimmed off of the finished part.

Equipment

The equipment used in the drop forming process is commonly known as a power or drop hammer. These may be powered by air, hydraulics, or mechanics. Depending on how the machine is powered, the mass of the ram, and the drop height, the striking force can be anywhere from 11,000 to 425,000 pounds. The tools that are used, dies and punches, come in many different shapes and sizes, as well as materials. Examples of these shapes are flat and v-shaped which are used for open-die forging, and single or multiple-impression dies used for closed die-forging. The designs for the dies have many aspects to them that must be considered. They all must be properly aligned, they must be designed so the metal and the flash will flow properly and fill all the grooves, and special considerations must be made for supporting webs and ribs and the parting line location. The materials must also be selected carefully. Some factors that go into the material selection are cost, their ability to harden, their ability to withstand high pressures, hot abrasion, heat cracking, and other such things. The most common materials used for the tools are carbon steel and, in some cases, nickel based alloys.

Workpiece Materials

The materials that are used most commonly in drop forging are aluminum, copper, nickel, mild steel, stainless steel, and magnesium. Mild steel is the best choice, and magnesium generally performs pretty poorly as a drop forging material.



Forge fire



Brake Drum Coal Forge

Chapter-7

Cutting Fluid



Thin-wall milling of aluminum using a water-based cutting fluid on the milling cutter.

Cutting fluid is a type of coolant and lubricant designed specifically for metalworking and machining processes. There are various kinds of cutting fluids, which include oils, oil-water emulsions, pastes, gels, aerosols (mists), and air or other gases. They may be

made from petroleum distillates, animal fats, plant oils, water and air, or other raw ingredients. Depending on context and on which type of cutting fluid is being considered, it may be referred to as **cutting fluid**, **cutting oil**, **cutting compound**, **coolant**, or **lubricant**.

Most metalworking and machining processes can benefit from the use of cutting fluid, depending on workpiece material. A common exception to this is machining cast iron or brass, which are machined dry.

The properties that are sought after in a good cutting fluid are the ability to:

- keep the workpiece at a stable temperature (critical when working to close tolerances). Very warm is OK, but extremely hot or alternating hot-and-cold are avoided.
- maximize the life of the cutting tip by lubricating the working edge and reducing tip welding.
- ensure safety for the people handling it (toxicity, bacteria, fungi) and for the environment upon disposal.
- prevent rust on machine parts and cutters.

Functions

Cooling

Metal cutting operations involve generation of heat due to friction between the tool and the pieces and due to energy lost deforming the material. The surrounding air alone is a rather poor coolant for the cutting tool, because the rate of heat transfer is low. Ambient-air cooling is adequate for light cuts with periods of rest in between, such as are typical in maintenance, repair and operations (MRO) work or hobbyist contexts. However, for heavy cuts and constant use, such as in production work, more heat is produced per time period than ambient-air cooling can remove. It is not acceptable to introduce long idle periods into the cycle time to allow the air-cooling of the tool to "catch up" when the heat-removal can instead be accomplished with a flood of liquid, which can "keep up" with the heat generation.

Lubrication

Besides cooling, cutting fluids also aid the cutting process by lubricating the interface between the tool's cutting edge and the chip. By preventing friction at this interface, some of the heat generation is prevented. This lubrication also helps prevent the chip from being welded onto the tool, which interferes with subsequent cutting.

Extreme pressure additives are often added to cutting fluids to further reduce tool wear.

Delivery methods

Every conceivable method of applying cutting fluid (e.g., flooding, spraying, dripping, misting, brushing) can be used, with the best choice depending on the application and the equipment available. For many metal cutting applications the ideal has long been high-pressure, high-volume pumping to force a stream of liquid (usually an oil-water emulsion) directly into the tool-chip interface, with walls around the machine to contain the splatter and a sump to catch, filter, and recirculate the fluid. This type of system is commonly employed, especially in manufacturing. It is often not a practical option for MRO or hobbyist metalcutting, where smaller, simpler machine tools are used. Fortunately it is also not necessary in those applications, where heavy cuts, aggressive speeds and feeds, and constant, all-day cutting are not vital.

As technology continually advances, the flooding paradigm is no longer always the clear winner. It has been complemented since the 2000s by new permutations of liquid, aerosol, and gas delivery, such as MQL and through-the-tool-tip cryogenic cooling.

Types

Liquids

There are generally three types of liquids: mineral, semi-synthetic, and synthetic. Semi-synthetic and synthetic cutting fluids try to blend the best properties of oil into the best properties of water. They basically achieve this by allowing oil to emulsify into water. Some of these properties are: rust inhibition, tolerance of a wide range of water hardness (maintain pH stability around 9 to 10), ability to work with many metals, resist thermal breakdown, and environmental safety.

Water is a great conductor of heat but has drawbacks as a cutting fluid. It boils easily, promotes rusting of machine parts, and does not lubricate well. Therefore, other ingredients are necessary to create an optimal cutting fluid.

Mineral oils, which are petroleum-based, began in the late 19th century. They vary from the thick, dark, sulfur-rich cutting oils used in heavy industry to light, clear oils.

Semi-synthetic coolants are an emulsion or microemulsion of water with mineral oil. They began in the 1930s. A typical CNC usually uses emulsified coolant, which consists of a small amount of oil emulsified into a larger amount of water through the use of a detergent.

Synthetic coolants originated in the late 1950s and are usually water-based.

A hand-held refractometer is used to determine the mix ratio (also called concentration) of water soluble coolants. Numerous other test equipment are used to determine such things as acidity, and amount of conductivity.

Others include:

- Kerosene, rubbing alcohol, and 3-In-One Oil often give good results when working on aluminium.
- WD-40
- Dielectric fluid is the cutting fluid used in Electrical discharge machines (EDMs). It is usually deionized water or a high-flash-point kerosene. Intense heat is generated by the cutting action of the electrode (or wire) and the fluid is used to stabilise the temperature of the workpiece, along with flushing any eroded particles from the immediate work area. The dielectric fluid is nonconductive.
- Liquid- (water- or petroleum oil-) cooled water tables are used with the plasma arc cutting (PAC) process.

Pastes or gels

Cutting fluid may also take the form of a paste or gel when used for some applications, in particular hand operations such as drilling and tapping. In sawing metal with a bandsaw, it is common to periodically run a stick of paste against the blade. This product is similar in form factor to lipstick or beeswax. It comes in a cardboard tube, which gets slowly consumed with each application.

Aerosols (mists)

Some cutting fluids are used in aerosol (mist) form (air with tiny droplets of liquid scattered throughout). The main problems with mists have been that they are rather bad for the workers, who have to breathe the surrounding mist-tainted air, and that they often don't even work very well. Both of those problems come from the imprecise delivery that often puts the mist everywhere and all the time except at the cutting interface, during the cut—the one place and time where it's wanted. However, a newer form of aerosol delivery, MQL (minimum quantity of lubricant), avoids both of those problems. The delivery of the aerosol is directly through the flutes of the tool (it arrives directly through or around the insert itself—an ideal type of cutting fluid delivery that traditionally has been unavailable outside of a few contexts such as gun drilling or expensive, state-of-the-art liquid delivery in production milling). MQL's aerosol is delivered in such a precisely targeted way (with respect to both location and timing) that the net effect seems almost like dry machining from the operators' perspective. The chips generally seem like dry-machined chips, requiring no draining, and the air is so clean that machining cells can be stationed closer to inspection and assembly than before.

Air or other gases (e.g., nitrogen)

Ambient air, of course, was the original machining coolant. Compressed air, supplied through pipes and hoses from an air compressor and discharged from a nozzle aimed at the tool, is sometimes a useful coolant. The force of the decompressing air stream blows chips away, and the decompression itself has a slight degree of cooling action ($pV=nRT$; lowering the pressure lowers the temperature).

Liquid nitrogen, supplied in pressurized steel bottles, is sometimes used in similar fashion. In this case, the decompression is enough to provide a powerful refrigerating effect. For years this has been done (in limited applications) by flooding the work zone. Since 2005, this mode of coolant has been applied in a manner comparable to MQL (with through-the-spindle and through-the-tool-tip delivery). This refrigerates the body and tips of the tool to such a degree that it acts as a "thermal sponge", sucking up the heat from the tool–chip interface. This new type of nitrogen cooling is still under patent. Tool life has been increased by a factor of 10 in the milling of tough metals such as titanium and inconel.

Past practice

- In 19th-century machining practice, it was not uncommon to use plain water. This was simply a practical expedient to keep the cutter cool, regardless of whether it provided any lubrication at the cutting edge–chip interface. When one considers that high-speed steel (HSS) had not been developed yet, the need to cool the tool becomes all the more apparent. (HSS retains its hardness at high temperatures; other carbon tool steels do not.) An improvement was soda water, which better inhibited the rusting of machine slides. These options are generally not used today because better options are available.
- Lard was very popular in the past. It is used infrequently today, because of the wide variety of other options, but it is still an option.
- Old machine shop training texts speak of using red lead and white lead, often mixed into lard or lard oil. This practice is obsolete due to the toxicity of lead.
- From the mid-20th century to the 1990s, 1,1,1-trichloroethane was used as an additive to make some cutting fluids more effective. In shop-floor slang it was referred to as "one-one-one". It has been phased out because of its ozone-depleting and central nervous system-depressing properties.

Safety concerns

Cutting fluids present some mechanisms for causing illness or injury in workers. These mechanisms are based on the external (skin) or internal contact involved in machining work, including touching the parts and tooling; being splattered or splashed by the fluid; or having mist settle on the skin or enter the mouth and nose in the normal course of breathing.

The mechanisms include the chemical toxicity or physical irritating ability of:

- the fluid itself
- the metal particles (from previous cutting) that are borne in the fluid
- the bacterial or fungal populations that naturally tend to grow in the fluid over time
- the biocides that are added to inhibit those life forms
- the corrosion inhibitors that are added to protect the machine and tooling

- the tramp oils that result from the way oils (the lubricants for the slideways) inevitably finding their way into the coolant

The toxicity or irritating ability is usually not high, but it is sometimes enough to cause problems for the skin or for the tissues of the respiratory tract or alimentary tract (e.g., the mouth, larynx, esophagus, trachea, or lungs).

Some of the diagnoses that can result from the mechanisms explained above include irritant contact dermatitis; allergic contact dermatitis; occupational acne; tracheitis; esophagitis; bronchitis; asthma; allergy; hypersensitivity pneumonitis (HP); and worsening of pre-existing respiratory problems.

Safer cutting fluid formulations provide a resistance to tramp oils, allowing improved filtration separation without removing the base additive package. Room ventilation, splash guards on machines, and personal protective equipment (PPE) (such as safety glasses, respirator masks, and gloves) can mitigate hazards related to cutting fluids.

Bacterial growth is predominant in semi-synthetic and synthetic fluids. Tramp oil along with human hair or skin oil are some of the debris during cutting which accumulates and forms a layer on the top of the liquid; anaerobic bacteria proliferate due to a number of factors. An early sign of the need for replacement is the "Monday-morning smell" (due to lack of usage from Friday to Monday). Antiseptics are sometimes added to the fluid to kill bacteria. Such use must be balanced against whether the antiseptics will harm the cutting performance, workers' health, or the environment. Maintaining as low a fluid temperature as practical will slow the growth of microorganisms.

The discussion above could leave a reader with the mistaken idea that cutting fluid is "often extremely dangerous". That would be an exaggeration. In reality, cutting fluid exposure is like many exposures in life, such as second-hand tobacco smoke; ethanol ingestion; paint and thinner fumes; kitchen or bakery smoke; smoke from smelting, casting, forging, or welding; contact with animal manure in farming, veterinary work, or pest control work; or contact with sewage in plumbing or sewer work. Such exposures only cause acute illness or injury in occasional cases where some situational factor was "out of normal bounds". Rather, the main health risk is that of chronic illness from long-term occupational exposure. Most machinists work around cutting fluids for years without adverse effects. They generally don't worry about casual contact, and they use PPE to minimize it.

Degradation, replacement, and disposal

Cutting fluids degrade over time due to contaminants entering the lubrication system. A common type of degradation is the formation of *tramp oil*, also known as *sump oil*, which is unwanted oil that has mixed with cutting fluid. It originates as lubrication oil that seeps out from the slideways and washes into the coolant mixture, as the protective film with which a steel supplier coats bar stock to prevent rusting, or as hydraulic oil leaks. In

extreme cases it can be seen as a film or skin on the surface of the coolant or as floating drops of oil.

Skimmers are used to separate the tramp oil from the coolant. These are typically slowly rotating vertical discs that are partially submerged below the coolant level in the main reservoir. As the disc rotates the tramp oil clings to each side of the disc to be scraped off by two wipers, before the disc passes back through the coolant. The wipers are in the form a channel that then redirects the tramp oil to a container where it is collected for disposal. Floating weir skimmers are also used in these situation where temperature or the amount of oil on the water becomes excessive.

Since the introduction of CNC additives, the tramp oil in these systems can be managed more effectively through a continuous separation effect. The tramp oil accumulation separates from the aqueous or oil based coolant and can be easily removed with an absorbent.

Old, used cutting fluid must be disposed of when it is fetid or chemically degraded and has lost its usefulness. As with used motor oil or other wastes, its impact on the environment should be mitigated. Legislation and regulation specify how this mitigation should be achieved. Modern cutting fluid disposal involves techniques such as ultrafiltration using polymeric or ceramic membranes which concentrates the suspended and emulsified oil phase.

One shop's total costs for each instance of cutting fluid replacement came to USD 373, which included 2 hours of machine downtime (accounted at USD 50 per hour); 2 hours of labor (accounted at USD 12 per hour); USD 69 worth of new coolant concentrate (which is then mixed with water); and USD 3 per U.S. gallon for proper disposal of about 60 gallons (about 225 L) of coolant. Clearly, fluid formulations and machining practices that extend the working lifespan of each batch of coolant can be worth the costs of developing them.

Chapter-8

Architectural Metals and Mass Finishing

Architectural metals

Architectural metals used in buildings and structures comprise several distinctive metallic materials. Metals serve a wide variety of uses in the built landscape, including structural features, such as nails and trusses, as well as decorative features, such as doorknobs and cladding. Some metals discovered by early civilizations are still in use today. Scientific study has brought a greater understanding of the performance and limits of the various types of metals used in buildings.

Metal Types

Lead

The low melting point of lead permitted its use on a wide scale throughout human history. Water pipes were frequently constructed of lead, until its health hazards were publicized in the late 19th century.

Lead has been a popular roofing material for centuries, being used for roofing, flashing, gutters, downspouts, and conductor heads. Lead was best suited for low-pitched roofs, as steep roofs experienced creep. Lead roofs in regions with large temperature fluctuations, such as the mid-Atlantic states, experienced deterioration from constant expansion and contraction, called fatigue. Beginning in the 19th century, a roofing material called “terne” or “terneplate” was used, consisting of sheet iron or sheet steel coated with a lead-tin alloy. It is frequently confused with tinplate.

Lead was also frequently used for window comes, for use in skylights and stained glass. It was also used for small pieces of sculpture and garden ornamentation. Finally, lead was frequently added to paint, with red lead used as an anti-corrosive pigment for iron, and white lead used as paint for wooden houses. Lead-based paint was one of the most durable materials developed as a protective exterior coating. The use of lead paint has been restricted on most buildings, due to concerns of lead poisoning.

Tin

The principal architectural uses of tin fall into two categories: the alloying of tin with other metals such as copper to form bronze, and the coating of tin on harder metals, such as tinplated iron or steel. Architectural bronzes usually contain about 90% copper and 10% tin, although the content may vary widely. The term “tin ceiling” is a misnomer, as these decorative sheets were never tinned; they were almost always painted sheet iron or steel.

Tinplate was a type of architectural material consisting of sheet iron coated with tin. “Tin roofs,” a type of tinplate, was originally used for armor but eventually as a roofing material. Tinplate was also used for decoration, such as ornamental windows and door lintels. Although tinplate is still available today for roofing and flashing, it is generally considered expensive since the initial cost is more than that for common modern roofing types such as asphalt shingles or built-up roofs. However, since a well-maintained tinplate roof typically lasts several times longer than either of these types of roofing, it is more economical when the cost is prorated over the longer lifespan.

Zinc

Pure zinc was used for roofing in Belgium, France and Germany, where it replaced more expensive copper and lead in roofing. Starting in the 1820s, Belgian sheet zinc was imported in America, used by builders in New York City and elsewhere. Pure zinc is subject to creep at ordinary temperatures.

Zinc-coated metals were first patented in 1837, separately by M. Sorel in France and H. W. Crawford in England. The methods employed a “hot dipping” process to coat sheet iron with zinc. By 1839 “galvanized” sheet iron roofing was being used in New York City. The Merchant's Exchange in Manhattan was one of the first buildings to have both a galvanized roof and galvanized gutters. Some galvanized sheet roofing was pressed with designs, a mode very popular in the Victorian era.

Zinc was also cast for sculptures and decorative elements in Germany as early as 1832. Decorative architectural elements were frequently cast in zinc, since it molded readily, was inexpensive compared to stone, and could be painted to imitate more expensive metals.

Zinc oxide paints were nontoxic and resistant to pollution. They became commercially successful and readily available in America in about 1850 and used widely starting around the 1870s. They had the added benefit of being good inhibitors against rust on iron and steel.

During the early decades of the 20th century, the use of pure zinc roofing and ornament decreased in use in the United States. It is now back on the upswing and gaining popularity in its pure form (99.95%) for building materials. Zinc is still used in alloys such as brass and nickel silver, and in the electroplating of steel as well. Today,

galvanized steel and pure zinc material, usually Double Locked Standing Seam panels, are used for roofing a variety of buildings. Creep has been reduced by the introduction of titanium in most architectural zinc available in North America. Galvanized nails and sheet metal ducts are also common.

Copper and Copper Alloys

The “cupric” metals include copper and its alloys, especially bronze, an alloy of copper and tin, and brass, an alloy of copper and zinc. Copper is a very durable metal, withstanding corrosion when forming a green patina, copper sulfate. Sheet copper used as roofing is lighter than wooden shingles and much lighter than slate, tile, or lead. Roofing copper can be folded readily into waterproof seams, or shaped over curved frameworks for cupolas and domes.

The initial cost of copper was traditionally high, but its length of service more than compensated for the price. Copper could also be shaped to the bends and angles around chimneys and at roof edges and dormers. All nails, screws, bolts, and cleats used with sheet copper had to be made of copper or a copper alloy; otherwise “galvanic” action between the dissimilar metals would occur, causing deterioration.

Copper was also used for decorative purposes, including architectural ornaments or sculptures. A very famous example of this is the Statue of Liberty.

With aging it turns a deep light green color.

Nickel and Nickel Alloys

Although somewhat rare, nickel has been used for plating architectural details. Nickel is most frequently used for building components in the form of alloys: nickel silver, Monel metal, and stainless steel.

Nickel silver was originally called “German Silver,” until World War I. It has been called “white brass” but probably should be termed “nickel brass,” because it generally contains 75% copper, 20% nickel, and 5% zinc. Different percentages result in a range of colors, including silvery-white, yellow, slight blue, green or pink. Nickel silver hardware was popular in the United States during the Art Deco and Depression Modern periods. Architects and designers preferred nickel silver because it could take and retain appropriate finishes, and it resisted corrosion.

Monel metal is an alloy of approximately two-thirds nickel and one-third copper. It is similar to platinum in color. Monel pioneered many of the present uses of stainless steel. The first architectural use of Monel was for roofing of the Pennsylvania Railroad Terminal in New York City in 1909. In 1936, the copper roof on the New York City Public Library at Fifth Avenue and 42nd Street was replaced with a Monel metal roof. Its advantages as a roofing material included its ability to be brazed, welded, or soldered in place to provide a watertight, continuous cover. Monel was popular during the Art Deco

periods. During World War II, however, large quantities of nickel and copper had to be diverted to the war effort and the supply of Monel was greatly reduced. Following the war, stainless steel and aluminium replaced Monel because of lower production costs.

Iron and Iron Alloys

Iron has become an important architectural building component. It has been used in four common forms: wrought iron, cast iron, sheet iron, and steel.

Wrought iron was used for minor structural and decorative elements starting in the 18th century. Until the mid-19th century, the use of wrought iron in buildings was generally limited to small items such as tie rods, straps, nails, and hardware, or to decorative ironwork in balconies, railings fences and gates. Around 1850 its structural use became more widespread as iron mills began to roll rails, bulb-tees, and eventually I-beams. It was also used for decorative purposes, such as ornamental balconies or hardware. Since wrought iron is handmade, no two pieces are identical.

Cast iron was a major 19th century building material of the Industrial Revolution. Although brittle, it is remarkably strong in compression. It was frequently used for structural purposes, such as columns,, building fronts, domes and light courts. Decorative uses have included stairs, elevators, lintels, grilles, verandas, balconies, railings, fences, streetlights, and tombs. The Bradbury Building is one example of extensive decorative cast iron use. Today, cast iron is used for plumbing fixtures and piping in new construction, and its structural and decorative use is used occasionally through historic preservation practices.

Sheet iron can be subject to rapid corrosion, forming rust. Sheet iron was used throughout the 19th century, although it is not clear how widespread sheet iron roofs became. Pressed decorative sheet iron used for ceilings was frequently called a “tin ceiling,” although tin was generally not present for indoor uses.

Steel was introduced to the construction industry at the end of the 19th century. The development of structural steel in the mid-19th century allowed tall buildings to be constructed. Builders and manufacturers turned to steel, which was stronger than cast iron in compression and wrought iron in tension. when the Bessemer process was developed in England in 1856, and the open-hearth process was invented, steel was produced in a quantity that allowed it to be economical. Bridges, railroad companies, and skyscrapers were among the first large-scale uses of structural steel. Although iron and steel are not combustible, they lose strength in a fire if they are not protected from the heat. Almost all structural steel has to be “fireproofed” in some manner, utilizing a cladding of terra-cotta, tile, plaster- poured concrete, sprayed concrete, or sprayed insulation. Ferro concrete, also called reinforced concrete, was developed in the late 19th century when steel wire was added to concrete.

Decorative steels used in buildings include:

- Stainless steel, a chromium-nickel steel, developed between 1903 and 1912. Its most important property is its resistance to corrosion. It contains about 18% chromium and 8-12% nickel. Stainless steel is expensive, so it was used primarily as a nonstructural metal or where there is a high potential for corrosion. One of the most extensive early uses of stainless steel was in the Chrysler Building.
- Copper-bearing steels, containing from .15% to .25% copper, develop increased resistance to atmospheric corrosion, when compared to ordinary steel, by forming a protective oxide coating, having a uniform deep brown color and texture. Eero Saarinen experimented with the material in the Deere and Company building in 1964.

Aluminum

Aluminum was not available at a reasonable price or in sufficient quantities for general architectural use until after the beginning of the 20th century. Architectural use of aluminum increased in the 1920s, mainly for decorative detailing. It was used for roofing, flashing, gutters, downspouts, wall panels, and spandrels. Art Deco designs frequently used aluminum for ornamental features. The first extensive use of aluminum in construction was the Empire State Building, where the entire tower portion is aluminum, as well as many decorative features, such as the entrances, elevator doors, ornamental trim, and some 6,000 window spandrels. Today, aluminum is used frequently in construction except major structural members.

Mass finishing

Mass finishing is a group of manufacturing processes that allow large quantities of parts to be simultaneously finished. The goal of this type of finishing is to burnish, deburr, clean, radius, de-flash, descale, remove rust, polish, brighten, surface harden, prepare parts for further finishing, or break off die cast runners. The two main types of mass finishing are tumble finishing, also known as barrel finishing, and vibratory finishing. Both involve the use of a cyclical action to create grinding contact between surfaces. Sometimes the workpieces are finished against each other; however, usually a finishing medium is used. Mass finishing can be performed dry or wet; wet processes have liquid lubricants, cleaners, or abrasives, while dry processes do not. Cycle times can be as short as 10 minutes for nonferrous workpieces or as long as 2 hours for hardened steel.

Mass finishing processes can be configured as either batch systems, in which batches of workpieces are added, run, and removed before the next batch is run, or as continuous systems, in which the workpieces enter at one end and leave at the other end in the finished state. They may also be sequenced, which involves running the workpieces through multiple different mass finishing processes; usually, the finish becomes

progressively finer. Due to the random action of the processes, mass finishing is as much an art as it is a science.

Media

Media are designed for four things:

Cut

Media which cut can remove burrs and can smooth surfaces. As a carrier of abrasive grain, the large medium pieces effectively increase the impact force of the abrasive on the metal part to be cut, thereby improving the efficiency of the abrasive. Cutting media develop dull, matte surfaces.

Luster

Some grades of medium are designed to promote luster on the surface of metal parts. These products are generally non-abrasive or have a very low degree of abrasiveness. They deburr by peening, rather than actually removing the burr. Media selection, therefore, will control the degree of surface luster, making the part bright and shiny or developing a very matte, dull surface characterized by a completely random scratch pattern, or anything in between.

Part separation

A very important function of the medium is to separate parts during the deburring, cutting, surface improving or burnishing operations. The media:parts volume ratio is normally used to control the amount of part-on-part contact which will occur in a vibratory or tumble finishing operation. At low ratios, considerable part-on-part contact occurs, while at higher ratios part-on-part contact is limited.

Surface scrubbing

Media have the unique ability to scrub surfaces and physically assist compounds in their cleaning function. Both abrasive and non-abrasive media are effective in this. They can remove organic soils, scale, and other inorganic residues.

Media come in a wide range of materials in order to fulfill various needs.

Aluminum media

Aluminium media are typically cast parts and are available in a wide variety of shapes and sizes. Aluminum scrubs parts and can work in conjunction with cleaning compounds to clean parts. Since aluminum is fairly nonabrasive it tends to remove surface impurities without affecting the part's surface qualities. Its cost is typically higher than other cast media. Wear rates are lower than ceramic but higher than steel media.

Preformed ceramic media

Ceramic media are manufactured by mixing clay-like materials and water with abrasives, forming the mud into shapes, drying the shapes, and firing them at high temperatures to vitrify the binder. Many of these binders are porcelain-like in nature. Variability in these products occur both with the type of binder used, firing temperatures, the amount, size and type of abrasive grains they contain, and their uniformity of firing. This type of media today is the general workhorse of

mass finishing systems and is the type of medium generally used, because of its availability in a variety of shapes and sizes, low cost, and low wear rate.

Preformed resin-bonded media

Plastic or resin-bonded media utilize a wider range of abrasive types and sizes than preformed ceramics. The most popular grades are those using quartz as an abrasive. Aluminum oxide, silicon carbide and other abrasives are also used. Usually, low-cost polyester resins are employed as the binder and the various shapes are produced by casting. Resin bonded media is good for preparing a metal surface for plating.

Steel

Case hardened, stress-relieved steel preformed shapes are available in a variety of sizes and configurations. Balls, balls with flat spots, ovoids (footballs), diagonally cut wire similar to angle-cut cylinders, ball cones and cones (both of which are different than the general concept of cones) and pins are the most commonly used. Steel media weigh approximately 300 pounds per cubic foot and are expensive for initial installation, but, because of their minimal attrition rate and extreme cleanliness, are being more widely used for light deburring applications and cleaning. Compounds are available to keep steel burnishing media clean and bright for extended periods.

Synthetic random-shaped media

The most popular synthetic random media is fused aluminum oxide, which is available in a number of grades. The more loosely bound, coarse-grained materials are characterized by fast cut and high depreciation rates. Because of the dark color of fused aluminum oxide, the soil generated by this material is excessive in many applications. Fine-grained fused aluminum oxide is generally employed for burnishing and in this respect is unexcelled in many applications with the possible exception of steel. Where some light cutting is required, fine-grained aluminum oxide can develop a better luster on stainless steels and other hard surfaces than can be achieved with steel burnishing media.

Natural random-shaped media

River rock, granite, quartz, limestone, emery and other naturally occurring abrasive materials are also used in vibratory and tumble finishing applications. In general, these media are not very efficient in vibratory equipment because of their high attrition rates.

Cobmeal, walnut-shell flour, and related materials

These are used for drying applications because of the natural ability of these materials to absorb water from metal surfaces. These can also be blended with abrasives and used for fine-polishing applications in vibratory, barrel, or spindle finishing equipment.

Other

Shoe pegs, leather, carpet tacks, and many other solid materials have been used at one time or another in tumble or vibratory finishing for certain applications.

Compounds

Compounds are added to mass finishing processes to assist in deburring, burnishing, cutting, cleaning, descaling, and inhibiting corrosion. They may be liquids or dry powders. They are usually broken up into four types: deburring and finishing, burnishing, cleaning, and water stabilizing.

Deburring and finishing

These compounds are mainly designed to suspend the small particles created when deburring and abrading parts. They are also designed to keep workpieces clean and inhibit corrosion.

Burnishing

Burnishing compounds are designed to enhance brightness and to develop certain colors after mass finishing.

Cleaning

These compounds are usually dilute acids or soaps designed to remove soil, grease, or oil from the incoming parts. They also provide corrosion resistance for ferrous and non-ferrous parts.

Water stabilizers

These are used in conjunction with water to maintain a consistent water hardness and level of metal ions. This helps ensure consistent results from batch to batch.

Chapter-9

Casting (Metalworking)



Casting iron in a sand mold

In metalworking, **casting** involves pouring a liquid metal into a mold, which contains a hollow cavity of the desired shape, and then is allowed to solidify. The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process. Casting is most often used for making complex shapes that would be difficult or uneconomical to make by other methods.

The casting process is subdivided into two main categories: expendable and non-expendable casting. It is further broken down by the mold material, such as sand or metal, and pouring method, such as gravity, vacuum, or low pressure.

Terminology

Metal casting processes uses the following terminology:

- Pattern: An approximate duplicate of the final casting used to form the mold cavity.
- Molding material: The material that is packed around the pattern and then the pattern is removed to leave the cavity where the casting material will be poured.
- Flask: The rigid wood or metal frame that holds the molding material.
 - Cope: The top half of the pattern, flask, mold, or core.
 - Drag: The bottom half of the pattern, flask, mold, or core.
- Core: An insert in the mold that produces internal features in the casting, such as holes.
 - Core print: The region added to the pattern, core, or mold used to locate and support the core.
- Mold cavity: The combined open area of the molding material and core, there the metal is poured to produce the casting.
- Riser: An extra void in the mold that fills with molten material to compensate for shrinkage during solidification.
- Gating system: The network of connected channels that deliver the molten material to the mold cavities.
 - Pouring cup or pouring basin: The part of the gating system that receives the molten material from the pouring vessel.
 - Sprue: The pouring cup attaches to the sprue, which is the vertical part of the gating system. The other end of the sprue attaches to the runners.
 - Runners: The horizontal portion of the gating system that connects the sprues to the gates.
 - Gates: The controlled entrances from the runners into the mold cavities.
- Vents: Additional channels that provide an escape for gases generated during the pour.
- Parting line or parting surface: The interface between the cope and drag halves of the mold, flask, or pattern.
- Draft: The taper on the casting or pattern that allow it to be withdrawn from the mold
- Core box: The mold or die used to produce the cores.

Some specialized processes, such as die casting, use additional terminology.

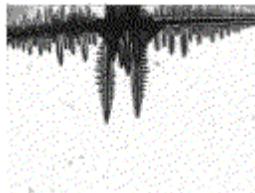
Theory

Casting is a solidification process, which means the solidification phenomenon controls most of the properties of the casting. Moreover, most of the casting defects occur during solidification, such as *gas porosity* and *solidification shrinkage*.

Solidification occurs in two steps: *nucleation* and *crystal growth*. In the nucleation stage solid particles form within the liquid. When these particles form their internal energy is lower than the surrounded liquid, which creates an energy interface between the two. The formation of the surface at this interface requires energy, so as nucleation occurs the material actually undercools, that is it cools below its freezing temperature, because of the extra energy required to form the interface surfaces. It then recalescences, or heats back up to its freezing temperature, for the crystal growth stage. Note that nucleation occurs on a pre-existing solid surface, because not as much energy is required for a partial interface surface, as is for a complete spherical interface surface. This can be advantageous because fine-grained castings possess better properties than coarse-grained castings. A fine grain structure can be induced by *grain refinement* or *inoculation*, which is the process of adding impurities to induce nucleation.

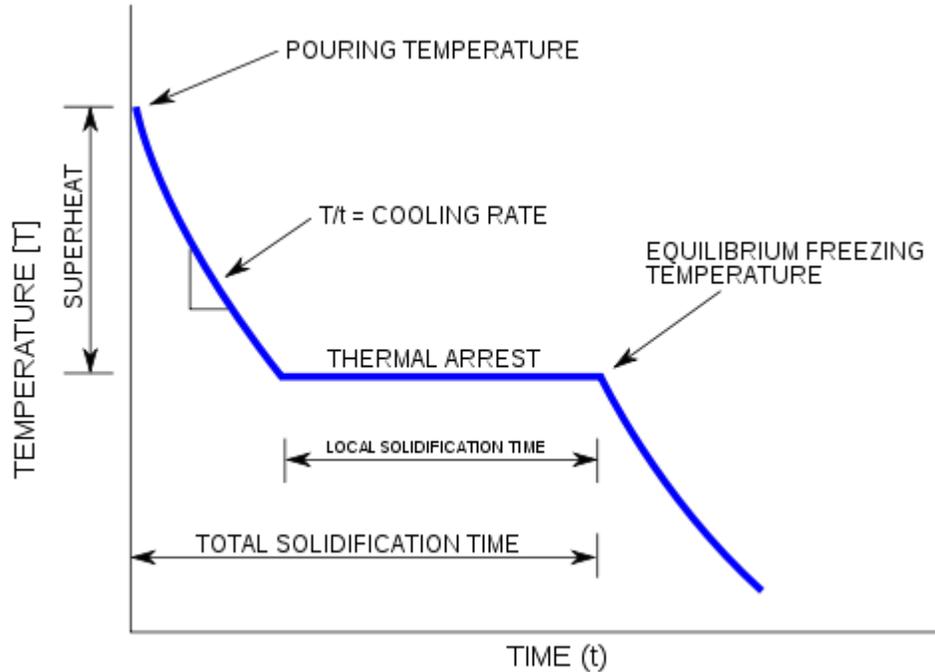
All of the nucleations represent a crystal, which grows as the heat of fusion is extracted from the liquid until there is no liquid left. The direction, rate, and type of growth can be controlled to maximize the properties of the casting. Directional solidification is when the material solidifies at one end and proceeds to solidify to the other end; this is the most ideal type of grain growth because it allows liquid material to compensate for shrinkage.

Cooling curves



Intermediate cooling rates from melt result in a dendritic microstructure. Primary and secondary dendrites can be seen in this image.

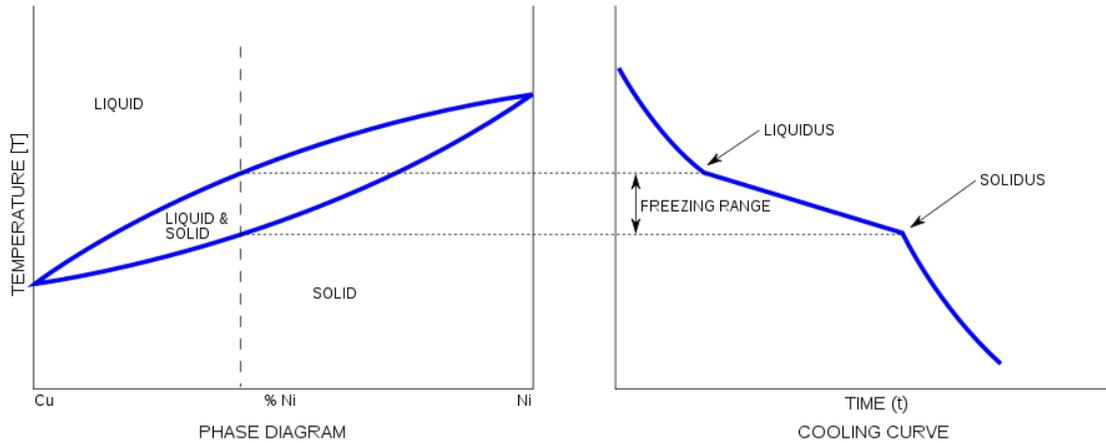
Cooling curves are important in controlling the quality of a casting. The most important part of the cooling curve is the *cooling rate* which affects the microstructure and properties. Generally speaking, an area of the casting which is cooled quickly will have a fine grain structure and an area which cools slowly will have a coarse grain structure. Below is an example cooling curve of a pure metal or eutectic alloy, with defining terminology.



Note that before the thermal arrest the material is a liquid and after it the material is a solid; during the thermal arrest the material is converting from a liquid to a solid. Also, note that the greater the superheat the more time there is for the liquid material to flow into intricate details.

The cooling rate is largely controlled by the mold material. When the liquid material is poured into the mold, the cooling begins. This happens because the heat within the molten metal flows into the relatively cooler parts of the mold. Molding materials transfer heat from the casting into the mold at different rates. For example, some molds made of plaster may transfer heat very slowly, while steel would transfer the heat quickly. Where heat should be removed quickly, the engineer will plan the mold to include special heat sinks to the mold, called chills. Fins may also be designed on a casting to extract heat, which are later removed in the cleaning (also called fettling) process. Both methods may be used at local spots in a mold where the heat will be extracted quickly. Where heat should be removed slowly, a riser or some padding may be added to a casting.

The above cooling curve depicts a basic situation with a pure alloy, however, most castings are of alloys, which have a cooling curve shaped as shown below.



Note that there is no longer a thermal arrest, instead there is a freezing range. The freezing range corresponds directly to the liquidus and solidus found on the phase diagram for the specific alloy.

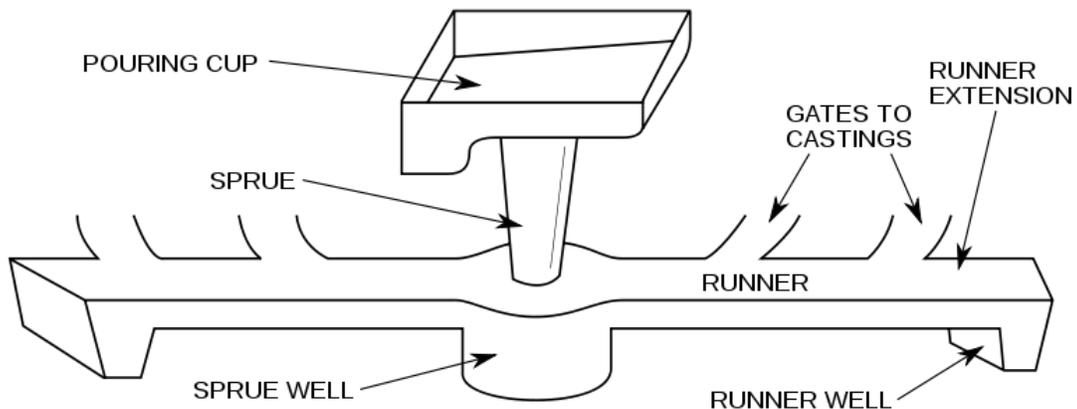
Chvorinov's rule

The local solidification time can be calculated using Chvorinov's rule, which is:

$$t = B \left(\frac{V}{A} \right)^n$$

Where t is the solidification time, V is the volume of the casting, A is the surface area of the casting that contacts the mold, n is a constant, and B is the mold constant. It is most useful in determining if a riser will solidify before the casting, because if the riser does solidify first then it is worthless.

The gating system



A simple gating system for a horizontal parting mold.

The gating system serves many purposes, the most important being conveying the liquid material to the mold, but also controlling shrinkage, the speed of the liquid, turbulence, and trapping dross. The gates are usually attached to the thickest part of the casting to assist in controlling shrinkage. In especially large castings multiple gates or runners may be required to introduce metal to more than one point in the mold cavity. The speed of the material is important because if the material is traveling too slowly it can cool before completely filling, leading to misruns and cold shuts. If the material is moving too fast then the liquid material can erode the mold and contaminate the final casting. The shape and length of the gating system can also control how quickly the material cools; short round or square channels minimize heat loss.

The gating system may be designed to minimize turbulence, depending on the material being cast. For example, steel, cast iron, and most copper alloys are turbulent insensitive, but aluminium and magnesium alloys are turbulent sensitive. The turbulent insensitive materials usually have a short and open gating system to fill the mold as quickly as possible. However, for turbulent sensitive materials short sprues are used to minimize the distance the material must fall when entering the mold. Rectangular pouring cups and tapered sprues are used to prevent the formation of a vortex as the material flows into the mold; these vortices tend to suck gas and oxides into the mold. A large sprue well is used to dissipate the kinetic energy of the liquid material as it falls down the sprue, decreasing turbulence. The *choke*, which is the smallest cross-sectional area in the gating system used to control flow, can be placed near the sprue well to slow down and smooth out the flow. Note that on some molds the choke is still placed on the gates to make separation of the part easier, but induces extreme turbulence. The gates are usually attached to the bottom of the casting to minimize turbulence and splashing.

The gating system may also be designed to trap dross. One method is to take advantage of the fact that some dross has a lower density than the base material so it floats to the top of the gating system. Therefore long flat runners with gates that exit from the bottom of the runners can trap dross in the runners; note that long flat runners will cool the material more rapidly than round or square runners. For materials where the dross is a similar density to the base material, such as aluminium, *runner extensions* and *runner wells* can be advantageous. These take advantage of the fact that the dross is usually located at the beginning of the pour, therefore the runner is extended past the last gate(s) and the contaminates are contained in the wells. Screens or filters may also be used to trap contaminates.

It is important to keep the size of the gating system small, because it all must be cut from the casting and remelted to be reused. The efficiency, or *yield*, of a casting system can be calculated by dividing the weight of the casting by the weight of the metal poured. Therefore, the higher the number the more efficient the gating system/risers.

Shrinkage

There are three types of shrinkage: *shrinkage of the liquid*, *solidification shrinkage* and *patternmaker's shrinkage*. The shrinkage of the liquid is rarely a problem because more

material is flowing into the mold behind it. Solidification shrinkage occurs because metals are less dense as a liquid than a solid, so during solidification the metal density dramatically increases. Patternmaker's shrinkage refers to the shrinkage that occurs when the material is cooled from the solidification temperature to room temperature, which occurs due to thermal contraction.

Solidification shrinkage

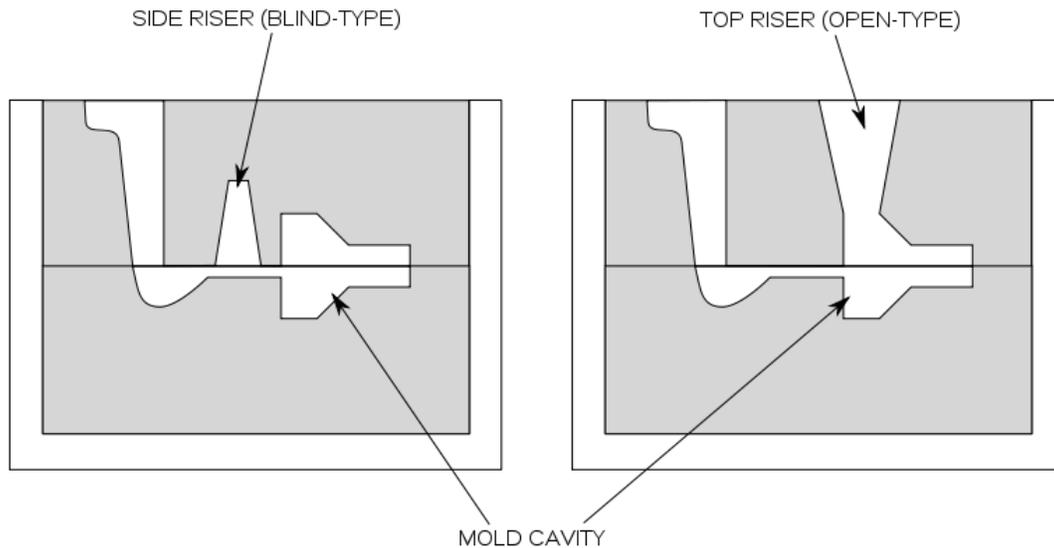
Solidification shrinkage of various metals

Metal	Percentage
Aluminium	6.6
Copper	4.9
Magnesium	4.0 or 4.2
Zinc	3.7 or 6.5
Low carbon steel	2.5–3.0
High carbon steel	4.0
White cast iron	4.0–5.5
Gray cast iron	–2.5–1.6
Ductile cast iron	–4.5–2.7

Most materials shrink as they solidify, but, as the table to the right shows, a few materials do not, such as gray cast iron. For the materials that do shrink upon solidification the type of shrinkage depends on how wide the freezing range is for the material. For materials with a narrow freezing range, less than 50 °C (122 °F), a cavity, known as a *pipe*, forms in the center of the casting, because the outer shell freezes first and progressively solidifies to the center. Pure and eutectic metals usually have narrow solidification ranges. These materials tend to form a *skin* in open air molds, therefore they are known as *skin forming alloys*. For materials with a wide freezing range, greater than 110 °C (230 °F), much more of the casting occupies the *mushy* or *slushy* zone (the temperature range between the solidus and the liquidus), which leads to small pockets of liquid trapped throughout and ultimately porosity. These castings tend to have poor ductility, toughness, and fatigue resistance. Moreover, for these types of materials to be fluid-tight a secondary operation is required to impregnate the casting with a lower melting point metal or resin.

For the materials that have narrow solidification ranges pipes can be overcome by designing the casting to promote directional solidification, which means the casting freezes first at the point farthest from the gate, then progressively solidifies towards the gate. This allows a continuous feed of liquid material to be present at the point of solidification to compensate for the shrinkage. Note that there is still a shrinkage void where the final material solidifies, but if designed properly this will be in the gating system or riser.

Risers and riser aids



Different types of risers

Risers, also known as *feeders*, are the most common way of providing directional solidification. It supplies liquid metal to the solidifying casting to compensate for solidification shrinkage. For a riser to work properly the riser must solidify after the casting, otherwise it cannot supply liquid metal to shrinkage within the casting. Risers add cost to the casting because it lowers the *yield* of each casting; i.e. more metal is lost as scrap for each casting. Another way to promote directional solidification is by adding chills to the mold. A chill is any material which will conduct heat away from the casting more rapidly than the material used for molding.

Risers are classified by three criteria. The first is if the riser is open to the atmosphere, if it is then it's called an *open riser*, otherwise it's known as a *blind type*. The second criterion is where the riser is located; if it is located on the casting then it is known as a *top riser* and if it is located next to the casting it is known as a *side riser*. Finally, if the riser is located on the gating system so that it fills after the molding cavity, it is known as a *live riser* or *hot riser*, but if the riser fills with materials that's already flowed through the molding cavity it is known as a *dead riser* or *cold riser*.

Riser aids are items used to assist risers in creating directional solidification or reducing the number of risers required. One of these items are *chills* which accelerate cooling in a certain part of the mold. There are two types: external and internal chills. External chills are masses of high-heat-capacity and high-thermal-conductivity material that are placed on an edge of the molding cavity. Internal chills are pieces of the same metal that is being poured, which are placed inside the mold cavity and become part of the casting. Insulating sleeves and toppings may also be installed around the riser cavity to slow the

solidification of the riser. Heater coils may also be installed around or above the riser cavity to slow solidification.

Patternmaker's shrink

Typical patternmaker's shrinkage of various metals

Metal	Percentage	in/ft
Aluminium	1.0–1.3	$\frac{1}{8}$ – $\frac{5}{32}$
Brass	1.5	$\frac{3}{16}$
Magnesium	1.0–1.3	$\frac{1}{8}$ – $\frac{5}{32}$
Cast iron	0.8–1.0	$\frac{1}{10}$ – $\frac{1}{8}$
Steel	2.5–3.0	$\frac{3}{16}$ – $\frac{1}{4}$

Shrinkage after solidification can be dealt with by using an oversized pattern designed specifically for the alloy used. *Contraction rules*, or *shrink rules*, are used to make the patterns oversized to compensate for this type of shrinkage. These rulers are up to 2% oversize, depending on the material being cast. These rulers are mainly referred to by their percentage change. A pattern made to match an existing part would be made as follows: First, the existing part would be measured using a standard ruler, then when constructing the pattern, the pattern maker would use a contraction rule, ensuring that the casting would contract to the correct size.

Note that patternmaker's shrinkage does not take phase change transformations into account. For example, eutectic reactions, martensitic reactions, and graphitization can cause expansions or contractions.

Mold cavity

The mold cavity of a casting does not reflect the exact dimensions of the finished part due to a number of reasons. These modifications to the mold cavity are known as *allowances* and account for patternmaker's shrinkage, draft, machining, and distortion. In non-expendable processes, these allowances are imparted directly into the permanent mold, but in expendable mold processes they are imparted into the patterns, which later form the mold cavity. Note that for non-expendable molds an allowance is required for the dimensional change of the mold due to heating to operating temperatures.

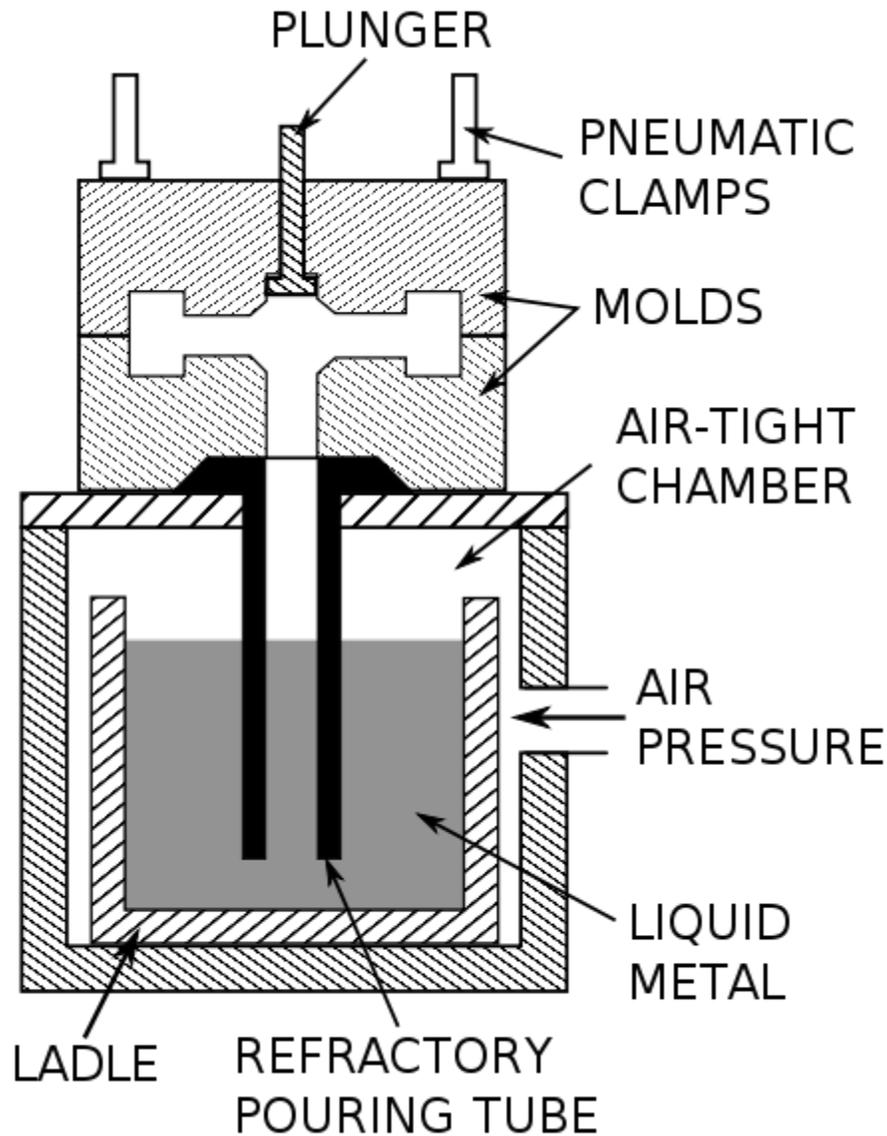
For surfaces of the casting that are perpendicular to the parting line of the mold a draft must be included. This is so that the casting can be released in non-expendable processes or the pattern can be released from the mold without destroying the mold in expendable processes. The required draft angle depends on the size and shape of the feature, the depth of the mold cavity, how the part or pattern is being removed from the mold, the pattern or part material, the mold material, and the process type. Usually the draft is not less than 1%.

The machining allowance varies drastically from one process to another. Sand castings generally have a rough surface finish, therefore need a greater machining allowance, whereas die casting has a very fine surface finish, which may not need any machining tolerance. Also, the draft may provide enough of a machining allowance to begin with.

The distortion allowance is only necessary for certain geometries. For instance, U-shaped castings will tend to distort with the legs splaying outward, because the base of the shape can contract while the legs are constrained by the mold. This can be overcome by designing the mold cavity to slope the leg inward to begin with. Also, long horizontal sections tend to sag in the middle if ribs are not incorporated, so a distortion allowance may be required.

Cores may be used in expendable mold processes to produce internal features. The core can be of metal but it is usually done in sand.

Filling



Schematic of the low-pressure permanent mold casting process

There are a few common methods for filling the mold cavity: *gravity*, *low-pressure*, *high-pressure*, and *vacuum*.

Vacuum filling, also known as *counter-gravity* filling, is more metal efficient than gravity pouring because less material solidifies in the gating system. Gravity pouring only has a 15 to 50% metal yield as compared to 60 to 95% for vacuum pouring. There is also less turbulence, so the gating system can be simplified since it does not have to control turbulence. Plus, because the metal is drawn from below the top of the pool the metal is free from dross and slag, as these are lower density (lighter) and float to the top of the

pool. The pressure differential helps the metal flow into every intricacy of the mold. Finally, lower temperatures can be used, which improves the grain structure. The first patented vacuum casting machine and process dates to 1879.

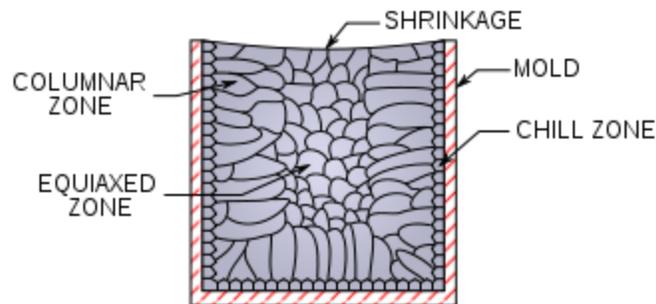
Low-pressure filling uses 5 to 15 psig (35 to 100 kPag) of air pressure to force liquid metal up a feed tube into the mold cavity. This eliminates turbulence found in gravity casting and increases density, repeatability, tolerances, and grain uniformity. After the casting has solidified the pressure is released and any remaining liquid returns to the crucible, which increases yield.

Tilt filling

Tilt filling, also known as *tilt casting*, is an uncommon filling technique where the crucible is attached to the gating system and both are slowly rotated so that the metal enters the mold cavity with little turbulence. The goal is to reduce porosity and inclusions by limiting turbulence. For most uses tilt filling is not feasible because of the following inherent problem: if the system is rotated slow enough to not induce turbulence, the front of the metal stream begins to solidify, which results in mis-runs. If the system is rotated faster then it induces turbulence, which defeats the purpose. Durville of France was the first to try tilt casting, in the 1800s. He tried to use it to reduce surface defects when casting coinage from aluminum bronze.

Macrostructure

The grain macrostructure in ingots and most castings have three distinct regions or zones: the chill zone, columnar zone, and equiaxed zone. The image below depicts these zones.



The chill zone is named so because it occurs at the walls of the mold where the wall *chills* the material. Here is where the nucleation phase of the solidification process takes place. As more heat is removed the grains grow towards the center of the casting. These are thin, long *columns* that are perpendicular to the casting surface, which are undesirable because they have anisotropic properties. Finally, in the center the equiaxed zone contains spherical, randomly oriented crystals. These are desirable because they have isotropic properties. The creation of this zone can be promoted by using a low pouring temperature, alloy inclusions, or inoculants.

Inspection

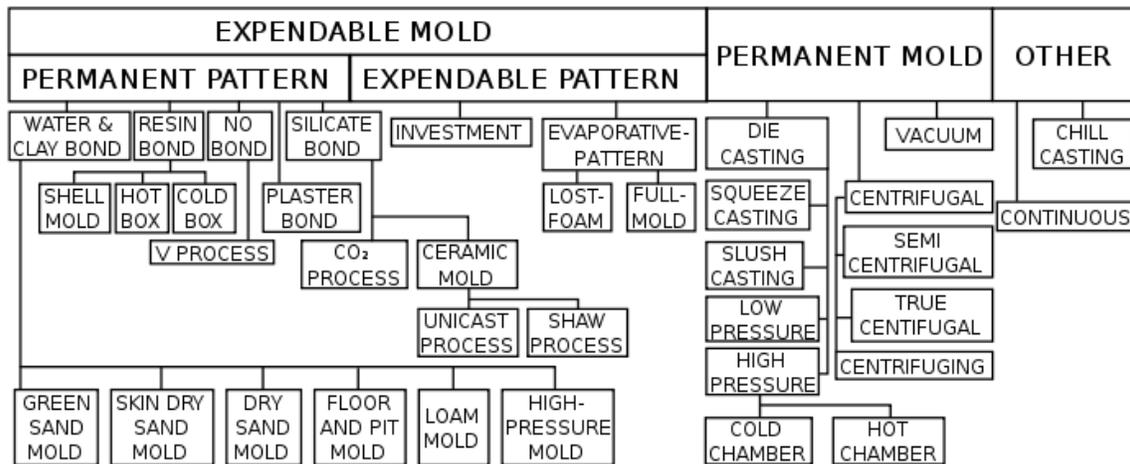
Common inspection methods for steel castings are *magnetic particle* and *liquid penetrant*. Common inspection methods for aluminum castings are *radiography*, *ultrasonic*, and *liquid penetrant*.

Defects

There are a number of problems that can be encountered during the casting process. The main types are: *gas porosity*, *shrinkage defects*, *mold material defects*, *pouring metal defects*, and *metallurgical defects*.

Expendable mold casting

Expendable mold casting is a generic classification that includes sand, plastic, shell, plaster, and investment (lost-wax technique) moldings. This method of mold casting involves the use of temporary, non-reusable molds.



Waste molding of plaster

A durable plaster intermediate is often used as a stage toward the production of a bronze sculpture or as a pointing guide for the creation of a carved stone. With the completion of a plaster, the work is more durable (if stored indoors) than a clay original which must be kept moist to avoid cracking. With the low cost plaster at hand, the expensive work of bronze casting or stone carving may be deferred until a patron is found, and as such work is considered to be a technical, rather than artistic process, it may even be deferred beyond the lifetime of the artist.

In waste molding a simple and thin plaster mold, reinforced by sisal or burlap, is cast over the original clay mixture. When cured, it is then removed from the damp clay, incidentally destroying the fine details in undercuts present in the clay, but which are now captured in the mold. The mold may then at any later time (but only once) be used to cast

a plaster positive image, identical to the original clay. The surface of this plaster may be further refined and may be painted and waxed to resemble a finished bronze casting.

Sand casting

Sand casting is one of the most popular and simplest types of casting that has been used for centuries. Sand casting allows for smaller batches to be made compared to permanent mold casting and at a very reasonable cost. Not only does this method allow manufacturers to create products at a low cost, but there are other benefits to sand casting, such as very small size operations. From castings that fit in the palm of your hand to train beds (one casting can create the entire bed for one rail car), it can all be done with sand casting. Sand casting also allows most metals to be cast depending on the type of sand used for the molds.

Sand casting requires a lead time of days for production at high output rates (1–20 pieces/hr-mold) and is unsurpassed for large-part production. Green (moist) sand has almost no part weight limit, whereas dry sand has a practical part mass limit of 2,300–2,700 kg (5,100–6,000 lb). Minimum part weight ranges from 0.075–0.1 kg (0.17–0.22 lb). The sand is bonded together using clays, chemical binders, or polymerized oils (such as motor oil). Sand can be recycled many times in most operations and requires little maintenance.

Plaster mold casting

Plaster casting is similar to sand casting except that plaster of paris is substituted for sand as a mold material. Generally, the form takes less than a week to prepare, after which a production rate of 1–10 units/hr-mold is achieved, with items as massive as 45 kg (99 lb) and as small as 30 g (1 oz) with very good surface finish and close tolerances. Plaster casting is an inexpensive alternative to other molding processes for complex parts due to the low cost of the plaster and its ability to produce near net shape castings. The biggest disadvantage is that it can only be used with low melting point non-ferrous materials, such as aluminium, copper, magnesium, and zinc.

Shell molding

Shell molding is similar to sand casting, but the molding cavity is formed by a hardened "shell" of sand instead of flask filled with sand. The sand is finer than sand casting sand and is mixed with a resin so that it can be heated by the pattern and harden into a shell around the pattern. Because of the resin it gives a much finer surface finish. The process is easily automated and more precise than sand casting. Common metals that are cast include cast iron, aluminium, magnesium, and copper alloys. This process is ideal for complex items that are small to medium sized.

Investment casting



An investment-cast valve cover

Investment casting (known as lost-wax casting in art) is a process that has been practised for thousands of years, with the lost-wax process being one of the oldest known metal forming techniques. From 5000 years ago, when beeswax formed the pattern, to today's high technology waxes, refractory materials and specialist alloys, the castings ensure high-quality components are produced with the key benefits of accuracy, repeatability, versatility and integrity.

Investment casting derives its name from the fact that the pattern is invested, or surrounded, with a refractory material. The wax patterns require extreme care for they are not strong enough to withstand forces encountered during the mold making. One advantage of investment casting is that the wax can be reused.

The process is suitable for repeatable production of net shape components from a variety of different metals and high performance alloys. Although generally used for small castings, this process has been used to produce complete aircraft door frames, with steel castings of up to 300 kg and aluminium castings of up to 30 kg. Compared to other casting processes such as die casting or sand casting, it can be an expensive process, however the components that can be produced using investment casting can incorporate intricate contours, and in most cases the components are cast near net shape, so requiring little or no rework once cast.

Evaporative-pattern casting

This is a class of casting processes that use pattern materials that evaporate during the pour, which means there is no need to remove the pattern material from the mold before casting. The two main processes are lost-foam casting and full-mold casting.

Lost-foam casting

Lost-foam casting is a type of evaporative-pattern casting process that is similar to investment casting except foam is used for the pattern instead of wax. This process takes advantage of the low boiling point of foam to simplify the investment casting process by removing the need to melt the wax out of the mold.

Full-mold casting

Full-mold casting is an evaporative-pattern casting process which is a combination of sand casting and lost-foam casting. It uses an expanded polystyrene foam pattern which is then surrounded by sand, much like sand casting. The metal is then poured directly into the mold, which vaporizes the foam upon contact.

Non-expendable mold casting



The permanent molding process

Non-expendable mold casting differs from expendable processes in that the mold need not be reformed after each production cycle. This technique includes at least four different methods: permanent, die, centrifugal, and continuous casting. This form of

casting also results in improved repeatability in parts produced and delivers Near Net Shape results.

Permanent mold casting

Permanent mold casting is metal casting process that employs reusable molds ("permanent molds"), usually made from metal. The most common process uses gravity to fill the mold, however gas pressure or a vacuum are also used. A variation on the typical gravity casting process, called slush casting, produces hollow castings. Common casting metals are aluminum, magnesium, and copper alloys. Other materials include tin, zinc, and lead alloys and iron and steel are also cast in graphite molds. Permanent molds, while lasting more than one casting still have a limited life before wearing out.

Die casting

The die casting process forces molten metal under high pressure into mold cavities (which are machined into dies). Most die castings are made from nonferrous metals, specifically zinc, copper, and aluminium based alloys, but ferrous metal die castings are possible. The die casting method is especially suited for applications where many small to medium sized parts are needed with good detail, a fine surface quality and dimensional consistency.

Semi-solid metal casting

Semi-solid metal (SSM) casting is a modified die casting process that reduces or eliminates the residual porosity present in most die castings. Rather than using liquid metal as the feed material, SSM casting uses a higher viscosity feed material that is partially solid and partially liquid. A modified die casting machine is used to inject the semi-solid slurry into re-usable hardened steel dies. The high viscosity of the semi-solid metal, along with the use of controlled die filling conditions, ensures that the semi-solid metal fills the die in a non-turbulent manner so that harmful porosity can be essentially eliminated.

Used commercially mainly for aluminium and magnesium alloys, SSM castings can be heat treated to the T4, T5 or T6 tempers. The combination of heat treatment, fast cooling rates (from using un-coated steel dies) and minimal porosity provides excellent combinations of strength and ductility. Other advantages of SSM casting include the ability to produce complex shaped parts net shape, pressure tightness, tight dimensional tolerances and the ability to cast thin walls.

Centrifugal casting

Centrifugal casting is both gravity- and pressure-independent since it creates its own force feed using a temporary sand mold held in a spinning chamber at up to 900 N. Lead time varies with the application. Semi- and true-centrifugal processing permit 30-50

pieces/hr-mold to be produced, with a practical limit for batch processing of approximately 9000 kg total mass with a typical per-item limit of 2.3-4.5 kg.

Industrially, the centrifugal casting of railway wheels was an early application of the method developed by German industrial company Krupp and this capability enabled the rapid growth of the enterprise.

Small art pieces such as jewelry are often cast by this method using the lost wax process, as the forces enable the rather viscous liquid metals to flow through very small passages and into fine details such as leaves and petals. This effect is similar to the benefits from vacuum casting, also applied to jewelry casting.

Continuous casting

Continuous casting is a refinement of the casting process for the continuous, high-volume production of metal sections with a constant cross-section. Molten metal is poured into an open-ended, water-cooled copper mold, which allows a 'skin' of solid metal to form over the still-liquid centre. The strand, as it is now called, is withdrawn from the mold and passed into a chamber of rollers and water sprays; the rollers support the thin skin of the strand while the sprays remove heat from the strand, gradually solidifying the strand from the outside in. After solidification, predetermined lengths of the strand are cut off by either mechanical shears or travelling oxyacetylene torches and transferred to further forming processes, or to a stockpile. Cast sizes can range from strip (a few millimetres thick by about five metres wide) to billets (90 to 160 mm square) to slabs (1.25 m wide by 230 mm thick). Sometimes, the strand may undergo an initial hot rolling process before being cut.

Continuous casting is used due to the lower costs associated with continuous production of a standard product, and also increases the quality of the final product. Metals such as steel, copper and aluminium are continuously cast, with steel being the metal with the greatest tonnages cast using this method.

Chapter-10

Riser (Casting) & Chill (Casting)

Riser (Casting)



A bronze casting showing the sprue and risers

A **riser**, also known as a **feeder**, is a reservoir built into a metal casting mold to prevent cavities due to shrinkage. Most metals are less dense as a liquid than as a solid so castings shrink upon cooling, which can leave a void at the last point to solidify. Risers prevent this by providing molten metal to the casting as it solidifies, so that the cavity forms in

the riser and not the casting. Risers are not effective on materials that have a large freezing range, because directional solidification is not possible. They are also not needed for casting processes that utilized pressure to fill the mold cavity. A feeder operated by a treadle is called an **underfeeder**.

The activity of planning of how a casting will be gated and risered is called *foundry methoding* or *foundry engineering*.

Theory

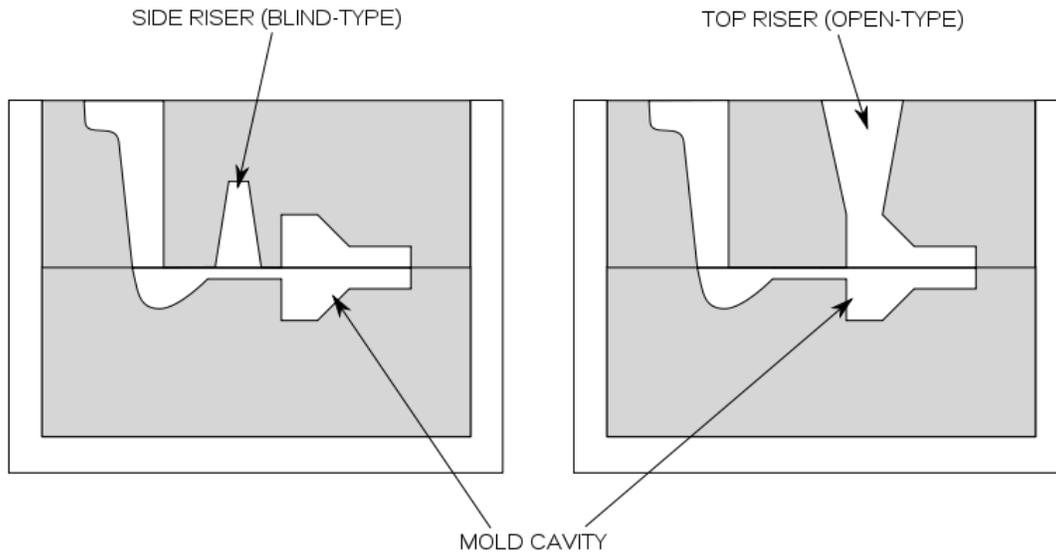
Risers are only effective if three conditions are met: the riser cools after the casting, the riser has enough material compensate for the casting shrinkage, and the casting directionally solidifies towards the riser.

For the riser to cool after the casting the riser must cool more slowly than the casting. Chvorinov's rule briefly states that the slowest cooling time is achieved with the greatest volume and the least surface area; geometrically speaking, this is a sphere. So, ideally, a riser should be a sphere, but this isn't a very practical shape to insert into a mold, so a cylinder is used instead. The height to diameter ratio of the cylinder varies depending on the material, location of the riser, size of the flask, etc.

The shrinkage must be calculated for the casting to confirm that there is enough material in the riser to compensate for the shrinkage. If it appears there is not enough material then the size of the riser must be increased. This requirement is more important for plate-like shapes, while the first requirement is more important for chunky shapes.

Finally, the casting must be designed to produce directional solidification, which sweeps from the extremities of the mold cavity toward the riser(s). In this way, the riser can feed molten metal continuously to part of the casting that is solidifying. One part of achieving this end is by placing the riser near the thickest and largest part of the casting, as that part of the casting will cool and solidify last. If this type of solidification is not possible, multiple risers that feed various sections of the casting or chills may be necessary.

Types



Different types of risers

Risers are categorized based on three criteria: location, if it is open to the atmosphere, and how it is filled. If the riser is located on the casting then it is known as a *top riser*, but if it is located next to the casting it is known as a *side riser*. Top risers are advantageous because they take up less space in the flask than a side riser, plus they have a shorter feeding distance. If the riser is open to the atmosphere it is known as an *open riser*, but if the riser is completely contained in the mold it is known as a *blind riser*. A blind riser is usually bigger than an open riser because the blind riser loses more heat to mold through the top of the riser. Finally, if the riser receives material from the gating system and fills after the mold cavity it is known as a *live riser* or *hot riser*. If the riser fills with material that has already flowed through the mold cavity it is known as a *dead riser* or *cold riser*. Live risers are usually smaller than dead risers. Note that top risers are almost always dead risers and risers in the gating system are almost always live risers.

Note that the connection of the riser to the molding cavity can be an issue for side risers. On one hand the connection should be as small as possible to make separation as easy as possible, but, on the other, the connection must be big enough for it to not solidify before the riser. The connection is usually made short to take advantage of the heat of both the riser and the molding cavity, which will keep it hot throughout the process.

There are risering aids that can be implemented to slow the cooling of a riser or decrease its size. One is using an insulating sleeve and top around the riser. Another is placing a heater around only the riser.

Hot tops

A *hot top*, also known as a *feeder head*, is a specialized riser that is used when casting ingots. It is essentially a live open riser, except a hot ceramic liner is used instead of just the mold material. The ingot is mostly poured and then the hot top is placed at the top of the mold. The rest of the metal is then poured. This keeps piping to a minimum. Robert Forester Mushet invented the hot top, but then called it a *dozzle*. With a hot top only 1 to 2% of the ingot is waste, prior up to 25% of the ingot was wasted.

Yield

The efficiency, or *yield*, of a casting is defined as the weight of the casting divided by the weight of the total amount of metal poured. Risers can add a lot to the total weight being poured, so it is important to optimize their size and shape. Because risers exist only to ensure the integrity of the casting, they are removed after the part has cooled, and their metal is remelted to be used again. As a result, riser size, number, and placement should be carefully planned to reduce waste while filling all the shrinkage in the casting.

One way to calculate the minimum size of a riser is to use Chvorinov's rule by setting the solidification time for the riser to be longer than that of the casting. Any time can be chosen but 25% longer is usually a safe choice, which is written as follows:

$$t_{\text{riser}} = 1.25t_{\text{casting}}$$

or

$$\left(\frac{V}{A}\right)_{\text{riser}}^n = 1.25 \left(\frac{V}{A}\right)_{\text{casting}}^n$$

Because all of the mold and material factors are the same for n . If a cylinder is chosen for the geometry of the riser and the height to diameter ratio is locked, then the equation can be solved for a diameter, which makes this method a simple way to calculate the minimum size for a riser. Note that if a top riser is used the surface area that is shared between the riser and the casting should be subtracted from the area on the casting and the riser.

Chill (casting)

A **chill** is an object used to promote solidification in a specific portion of a metal casting mold. Normally the metal in the mold cools at a certain rate relative to thickness of the casting. When the geometry of the molding cavity prevents directional solidification from occurring naturally, a chill can be strategically placed to help promote it. There are two types of chills: *internal* and *external* chills.

Types

Internal chills are pieces of metal that are placed inside the molding cavity. When the cavity is filled, part of the chill will melt and ultimately become part of the casting, thus the chill must be the same material as the casting. Note that internal chills will absorb both heat capacity and heat of fusion energy.

External chills are masses of material that have a high heat capacity and thermal conductivity. They are placed on the edge of the molding cavity, and effectively become part of the wall of the molding cavity. This type of chill can be used to increase the feeding distance of a riser or reduce the number of risers required.

Materials

A chill that is commonly used in sand castings is made of iron, which has a higher density, thermal conductivity and thermal capacity than the mold material. Chills can be made of many materials, including iron, copper, bronze, aluminium, graphite, and silicon carbide. Other sand materials with higher densities, thermal conductivity or thermal capacity can also be used as a chill. For example, chromite sand or zircon sand can be used when molding with silica sand.

Chapter-11

Full-Mold Casting & Semi-Solid Metal Casting

Full-Mold Casting

Full-mold casting is a evaporative-pattern casting process which is a combination of sand casting and lost-foam casting. It uses a expanded polystyrene foam pattern which is then surrounded by sand, much like sand casting. The metal is then poured directly into the mold, which vaporizes the foam upon contact.

Process

First, a pattern is made from polystyrene foam, which can be done many different ways. For small volume runs the pattern can be hand cut or machined from a solid block of foam; if the geometry is simple enough it can even be cut using a hot-wire foam cutter. If the volume is large, then the pattern can be mass-produced by a process similar to injection molding. Pre-expanded beads of polystyrene are injected into a preheated aluminium mold at low pressure. Steam is then applied to the polystyrene which causes it to expand more to fill the die. The final pattern is approximately 97.5% air and 2.5% polystyrene. Once the pattern is made pre-made pouring basins, runners, and risers can be hot glued to form the final pattern.

The pattern is then coated with a refractory material. The coated pattern is then placed in a flask and packed carefully with green sand or a chemically bonded sand. Finally, the molten metal is poured into the mold, which vaporizes the foam allowing the metal to fill the entire mold. The casting is allowed to cool and then dumped out of the flask ready to use. The sand does not need to be reprocessed so it can be directly reused.

Details

The minimum wall thickness for a full-mold casting is 2.5 mm (0.10 in). Typical dimensional tolerances are 0.3% and typical surface finishes are from 2.5 to 25 μm (100 to 1000 μin) RMS. The size range is from 400 g (0.88 lb) to several tonnes (tons).

Full-mold casting is often used to produce cylinder heads, engine blocks, pump housings, automotive brake components, and manifolds. Commonly employed materials include aluminium, iron, steel, nickel alloys, and copper alloys.

Advantages and disadvantages

This casting process is advantageous for very complex castings, that would regularly require cores. It is also dimensionally accurate, requires no draft, and has no parting lines so no flash is formed. As compared to investment casting, it is cheaper because it is a simpler process and the foam is cheaper than the wax. Risers are not usually required due to the nature of the process; because the molten metal vaporizes the foam the first metal into the mold cools more quickly than the rest, which results in natural directional solidification.

The two main disadvantages are that pattern costs can be high for low volume applications and the patterns are easily damaged or distorted due to their low strength. If a die is used to create the patterns there is a large initial cost.

History

The first patent for an evaporative-pattern casting process was filed in April 1956, by H.F. Shroyer. He patented the use of foam patterns embedded in traditional green sand for metal casting.

Semi-Solid Metal Casting

Semi-solid metal casting (SSM) is a near net shape variant of die casting. The process is used with non-ferrous metals, such as aluminium, copper, and magnesium. The process combines the advantages of casting and forging. The process is named after the fluid property thixotropy, which is the phenomenon that allows this process to work. Simply, thixotropic fluids shear when the material flows, but thicken when standing. The potential for this type of process was first recognized in the early 1970s. There are four different processes: *thixocasting*, *rheocasting*, *thixomolding*, and *SIMA*.

SSM is done at a temperature that puts the metal between its liquidus and solidus temperature. Ideally, the metal should be 30 to 65% solid. The metal must have a low viscosity to be usable, and to reach this low viscosity the material needs a globular primary surrounded by the liquid phase. The temperature range possible depends on the material and for aluminum alloys is 5-10°C, but for narrow melting range copper alloys can be only several tenths of a degree.

Semi-solid casting is typically used for high-end castings. For aluminum alloys typical parts include engine suspension mounts, air manifold sensor harness, engine blocks and oil pump filter housing.

Processes

There are a number of different techniques to produce semi-solid castings. For aluminum alloys the more common processes are *thixocasting* and *rheocasting*. Other process such as *strain induced melt activation (SIMA)* and *RAP* can also be used with aluminum alloys, although are less common commercially.

With magnesium alloys, the most common process is *thixomolding*.

Thixocasting

Thixocasting utilizes a pre-cast billet with a non-dendritic microstructure that is normally produced by vigorously stirring the melt as the bar is being cast. Induction heating is normally used to re-heat the billets to the semi-solid temperature range, and die casting machines are used to inject the semi-solid material into hardened steels dies.

Thixocasting is being performed commercially in North America, Europe and Asia. Thixocasting has the ability to produce extremely high quality components due to the product consistency that results from using pre-cast billet that is manufactured under the same ideal continuous processing conditions that are employed to make forging or rolling stock. The main disadvantage is that it is expensive due to the special billets that must be used. Other disadvantages include a limited number of alloys, and scrap cannot be directly reused.

Rheocasting

Unlike thixocasting, which re-heats a billet, rheocasting develops the semi-solid slurry from the molten metal produced in a typical die casting furnace/machine. This is a big advantage over thixocasting because it results in less expensive feedstock, in the form of typical die casting alloys, and allows for direct recycling.

There are a large number of rheocasting processes that have been proposed over the past ten years or so, and they generally differ in the method used to generate the semi-solid slurry. 18 different rheocasting techniques were documented in a recent publication. The first commercial rheocasting process was the *New Rheocasting Process (NRC)* developed by Ube Industries.

Thixomolding

For magnesium alloys, thixomolding uses a machine similar to injection molding. In a single step process, room temperature magnesium alloy chips are fed into the back end of a heated barrel through a volumetric feeder. The barrel is maintained under an argon atmosphere to prevent oxidation of the magnesium chips. A screw feeder located inside

the barrel feeds the magnesium chips forward as they are heated into the semi-solid temperature range. The screw rotation provides the necessary shearing force to generate the globular structure needed for semi-solid casting. Once enough slurry has accumulated, the screw moves forward to inject the slurry into a steel die.

SIMA

In the SIMA method the material is first heated to the SMM temperature. As it nears the solidus temperature the grains recrystallize to form a fine grain structure. After the solidus temperature is passed the grain boundaries melt to form the SSM microstructure. For this method to work the material should be extruded or cold rolled in the half-hard tempered state. This method is limited in size to bar diameters smaller than 37 mm (1.5 in); because of this only smaller parts can be cast.

Advantages and disadvantages

The advantages of semi-solid casting are as follows:

- Complex parts produced net shape
- Porosity free
- Excellent mechanical performance
- Pressure tightness
- Tight tolerances
- Thin walls
- Heat treatable (T4/T5/T6)

Due to the lower pressures and temperatures required to die cast semi-solid metal the die material does not need to be as exotic. Oftentimes graphite or softer stainless steels are used. Even non-ferrous dies can be used for one time shots. Because of this the process can be applied to rapid prototyping needs and mass production. This also allows for the casting of high melting point metals, such as tool steel and stellite, if a higher temperature die material is used. Other advantages include: easily automated, consistent, production rates are equal to or better than die casting rates, no air entrapment, low shrinkage rates, and a uniform microstructure.

The disadvantages to SSM are: high cost of raw material due to a low number of suppliers, higher die development costs, and operators require a higher level of training. SSM cannot cast as complex or thin of parts as high-pressure die casting, however in thicker walled castings SSM has less porosity.

Chapter-12

Permanent Mold Casting



Permanent mold casting

Permanent mold casting is metal casting process that employs reusable molds ("permanent molds"), usually made from metal. The most common process uses gravity to fill the mold, however gas pressure or a vacuum are also used. A variation on the typical gravity casting process, called **slush casting**, produces hollow castings. Common casting metals are aluminum, magnesium, and copper alloys. Other materials include tin, zinc, and lead alloys and iron and steel are also cast in graphite molds.

Typical parts include gears, splines, wheels, gear housings, pipe fittings, fuel injection housings, and automotive engine pistons.

Process

There are four main types of permanent mold casting: gravity, slush, low-pressure, and vacuum.

Gravity process

The gravity process begins by preheating the mold to 150-200 °C (300-400 °F) to ease the flow and reduce thermal damage to the casting. The mold cavity is then coated with a refractory material or a mold wash, which prevents the casting from sticking to the mold and prolongs the mold life. Any sand or metal cores are then installed and the mold is clamped shut. Molten metal is then poured into the mold. Soon after solidification the mold is opened and the casting removed to reduce chances of hot tears. The process is then started all over again, but preheating is not required because the heat from the previous casting is adequate and the refractory coating should last several castings. Because this process is usually carried out on large production run workpieces automated equipment is used to coat the mold, pour the metal, and remove the casting.

The metal is poured at the lowest practical temperature in order to minimize cracks and porosity. The pouring temperature can range greatly depending on the casting material; for instance zinc alloys are poured at approximately 700 °F (371 °C), while gray iron is poured at approximately 2,500 °F (1,370 °C).

Mold

Molds for the casting process consist of two halves. Casting molds are usually formed from gray cast iron because it has about the best thermal fatigue resistance, but other materials include steel, bronze, and graphite. These metals are chosen because of their resistance to erosion and thermal fatigue. They are usually not very complex because the mold offers no collapsibility to compensate for shrinkage. Instead the mold is opened as soon as the casting is solidified, which prevents hot tears. Cores can be used and are usually made from sand or metal.

As stated above, the mold is heated prior to the first casting cycle and then used continuously in order to maintain as uniform a temperature as possible during the cycles.

This decreases thermal fatigue, facilitates metal flow, and helps control the cooling rate of the casting metal.

Venting usually occurs through the slight crack between the two mold halves, but if this is not enough then very small vent holes are used. They are small enough to let the air escape but not the molten metal. A riser must also be included to compensate for shrinkage. This usually limits the yield to less than 60%.

Mechanical ejectors in the form of pins are used when coatings are not enough to remove casts from the molds. These pins are placed throughout the mold and usually leave small round impressions on the casting.

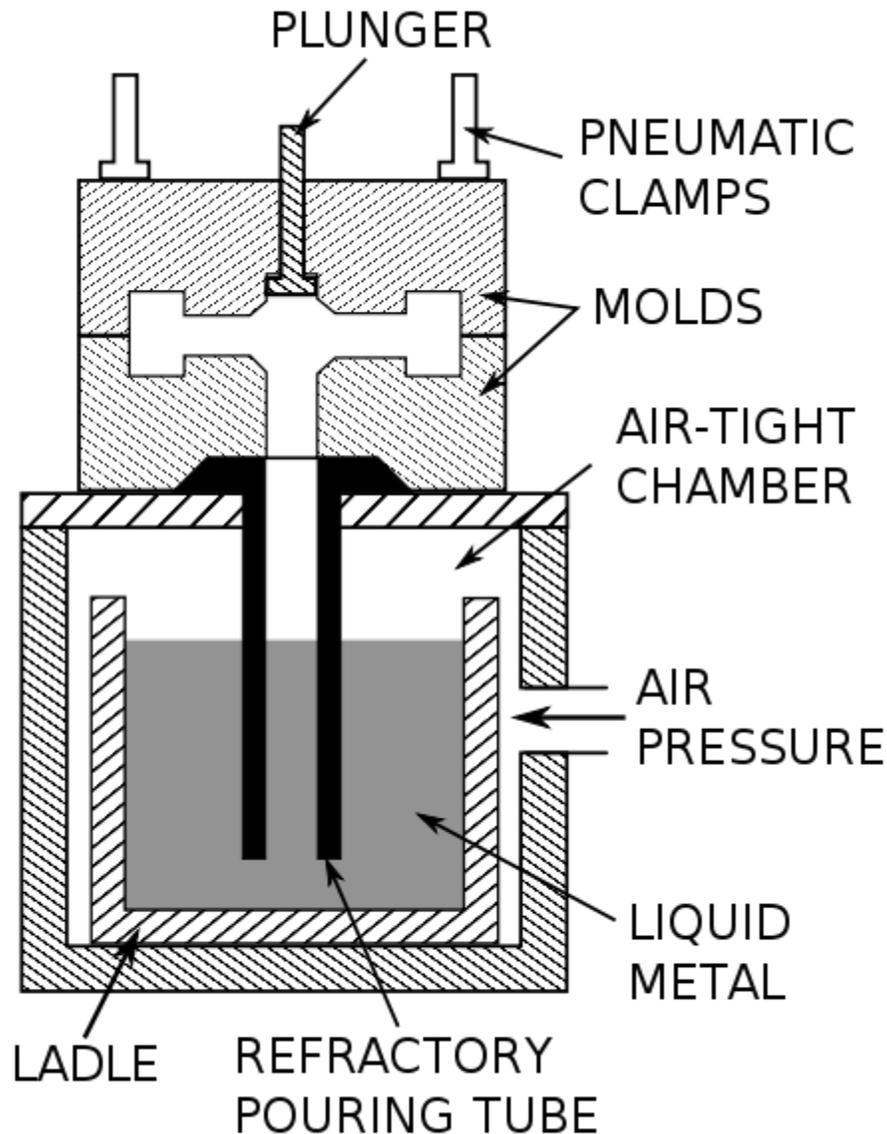
Slush

Slush casting is a variant of permanent molding casting to create a *hollow casting* or *hollow cast*. In the process the material is poured into the mold and allowed to cool until a shell of material forms in the mold. The remaining liquid is then poured out to leave a hollow shell. The resulting casting has good surface detail but the wall thickness can vary. The process is usually used to cast ornamental products, such as candlesticks, lamp bases, and statuary, from low-melting-point materials. A similar technique is used to make hollow chocolate figures for Easter and Christmas.

The method was developed by William Britain in 1893 for the production of lead toy soldiers. It uses less material than solid casting, and results in a lighter and less expensive product. Hollow cast figures generally have a small hole where the excess liquid was poured out.

Hollow casting is also used extensively for vitreous china products, such as sinks, urinals, and toilets.

Low-pressure



Schematic of the low-pressure permanent mold casting process

Low-pressure permanent mold (*LPPM*) casting uses a gas at low pressure, usually between 3 and 15 psig (20 to 100 kPag) to push the molten metal into the mold cavity. The pressure is applied to the top of the pool of liquid, which forces the molten metal up a refractory pouring tube and finally into the bottom of the mold. The pouring tube extends to the bottom of the ladle so that the material being pushed into the mold is exceptionally clean. No risers are required because the applied pressure forces molten metal in to compensate for shrinkage. Yields are usually greater than 85% because there is no riser and any metal in the pouring tube just falls back into the ladle for reuse.

The vast majority of LPPM casting are from aluminum and magnesium, but some are copper alloys. Advantages include very little turbulence when filling the mold because of the constant pressure, which minimizes gas porosity and dross formation. Mechanical properties are about 5% better than gravity permanent mold castings. The disadvantage is that cycles times are longer than gravity permanent mold castings.

Vacuum

Vacuum permanent mold casting retains all of the advantages of LPPM casting, plus the dissolved gases in the molten metal are minimized and molten metal cleanliness is even better. The process can handle thin-walled profiles and gives an excellent surface finish. Mechanical properties are usually 10 to 15% better than gravity permanent mold castings. The process is limited in weight to 0.2 to 5 kg (0.44 to 11 lb).

Advantages and disadvantages

The main advantages are the reusable mold, good surface finish, and good dimensional accuracy. Typical tolerances are 0.4 mm for the first 25 mm (0.015 in for the first inch) and 0.02 mm for each additional centimeter (0.002 in per in); if the dimension crosses the parting line add an additional 0.25 mm (0.0098 in). Typical surface finishes are 2.5 to 7.5 μm (100–250 μin) RMS. A draft of 2 to 3° is required. Wall thicknesses are limited to 3 to 50 mm (0.12 to 2.0 in). Typical part sizes range from 100 g to 75 kg (several ounces to 150 lb). Other advantages include the ease of inducing directional solidification by changing the mold wall thickness or by heating or cooling portions of the mold. The fast cooling rates created by using a metal mold results in a finer grain structure than sand casting. Retractable metal cores can be used to create undercuts while maintaining a quick action mold.

There are three main disadvantages: high tooling cost, limited to low-melting-point metals, and short mold life. The high tooling costs make this process uneconomical for small production runs. When the process is used to cast steel or iron the mold life is extremely short. For lower melting point metals the mold life is longer but thermal fatigue and erosion usually limit the life to 10,000 to 120,000 cycles. The mold life is dependent on four factors: the mold material, the pouring temperature, the mold temperature, and the mold configuration. The pouring temperature is dependent on the casting metal, but the higher the pouring temperature the shorter the mold life. A high pouring temperature can also induce shrinkage problems and create longer cycle times. If the mold temperature is too low misruns are produced, but if the mold temperature is too high then the cycle time is prolonged and mold erosion is increased. Large differences in section thickness in the mold or casting can decrease mold life as well.

Chapter-13

Sand Casting

Sand casting, also known as **sand molded casting**, is a metal casting process characterized by using sand as the mold material.

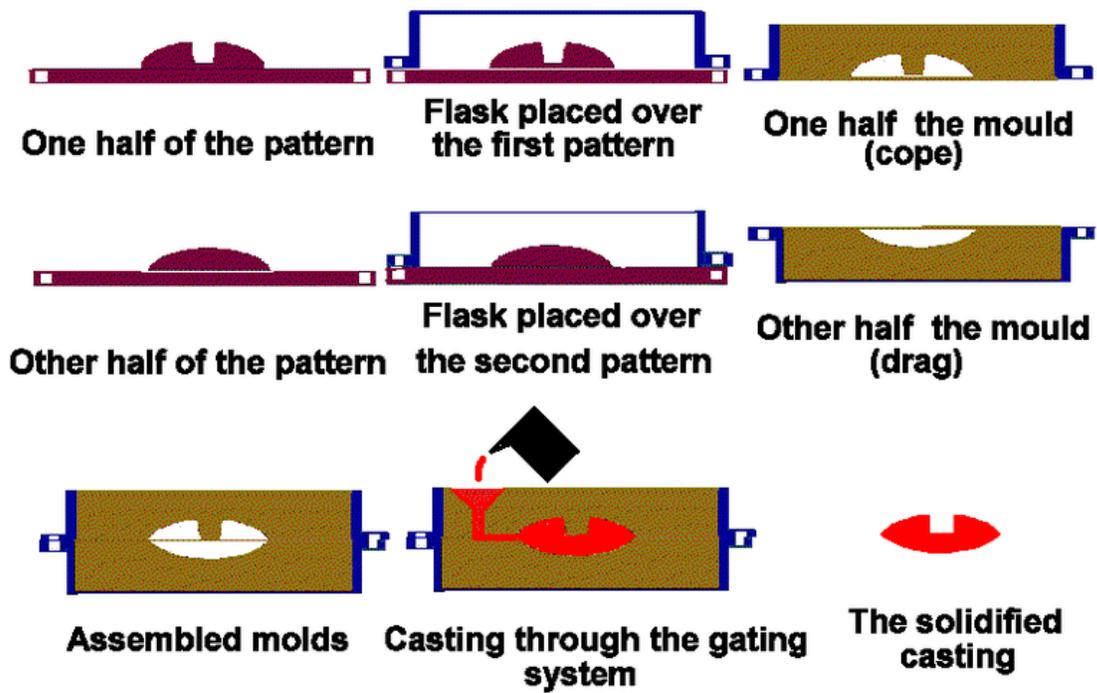
It is relatively cheap and sufficiently refractory even for steel foundry use. A suitable bonding agent (usually clay) is mixed or occurs with the sand. The mixture is moistened with water to develop strength and plasticity of the clay and to make the aggregate suitable for molding. The term "sand casting" can also refer to a casting produced via the sand casting process. Sand castings are produced in specialized factories called foundries.

Over 70% of all metal castings are produced via a sand casting process.

Basic process

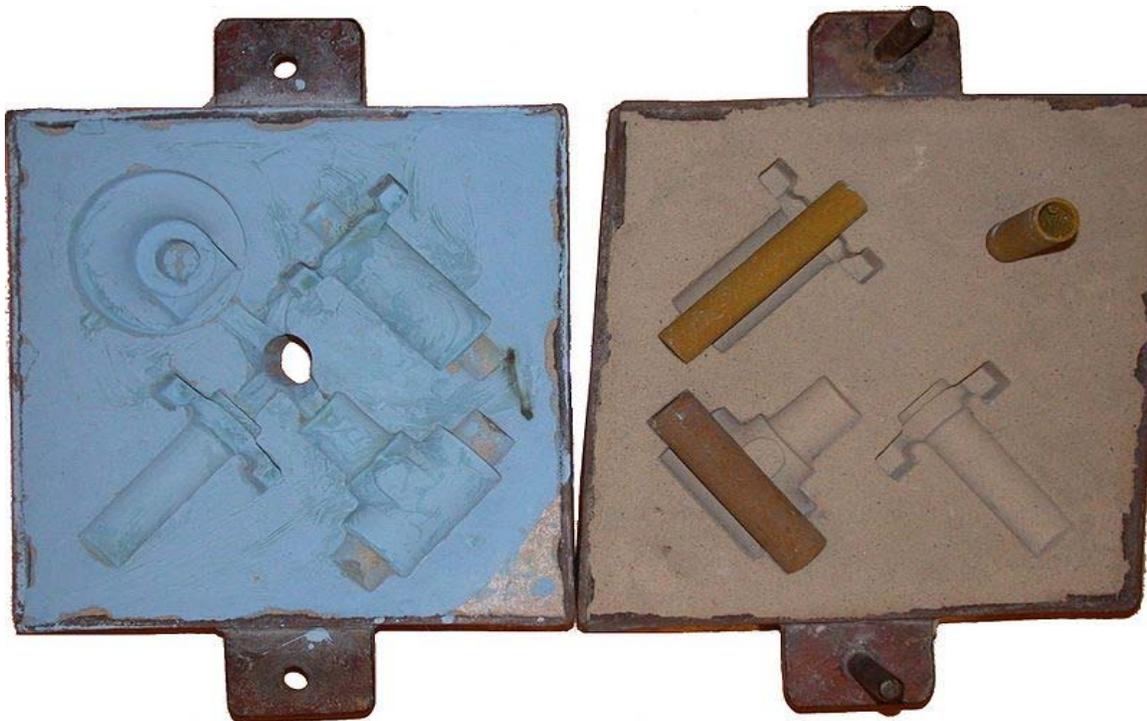
There are six steps in this process:

1. Place a pattern in sand to create a mold.
2. Incorporate the pattern and sand in a gating system.
3. Remove the pattern.
4. Fill the mold cavity with molten metal.
5. Allow the metal to cool.
6. Break away the sand mold and remove the casting.



Components

Patterns



Cope & drag (top and bottom halves of a sand mold), with cores in place on the drag

From the design, provided by an engineer or designer, a skilled *pattern maker* builds a *pattern* of the object to be produced, using wood, metal, or a plastic such as expanded polystyrene. Sand can be ground, swept or even strickled into shape. The metal to be cast will contract during solidification, and this may be non-uniform due to uneven cooling. Therefore, the pattern must be slightly larger than the finished product, a difference known as *contraction allowance*. Pattern-makers are able to produce suitable patterns using 'Contraction rules' (these are sometimes called "shrink allowance rulers" where the ruled markings are deliberately made to a larger spacing according to the percentage of extra length needed). Different scaled rules are used for different metals because each metal and alloy contracts by an amount distinct from all others. Patterns also have core prints that create registers within the molds into which are placed sand '*cores*'. Such cores, sometimes reinforced by wires, are used to create under cut profiles and cavities which cannot be molded with the cope and drag, such as the interior passages of valves or cooling passages in engine blocks.

Paths for the entrance of metal into the mold cavity constitute the runner system and include the sprue, various feeders which maintain a good metal 'feed', and in-gates which attach the runner system to the casting cavity. Gas and steam generated during casting exit through the permeable sand or via risers, which are added either in the pattern itself, or as separate pieces.

Molding box and materials

A multi-part molding box (known as a casting flask, the top and bottom halves of which are known respectively as the cope and drag) is prepared to receive the pattern. Molding boxes are made in segments that may be latched to each other and to end closures. For a simple object—flat on one side—the lower portion of the box, closed at the bottom, will be filled with a molding sand. The sand is packed in through a vibratory process called ramming and, in this case, periodically screeded level. The surface of the sand may then be stabilized with a sizing compound. The pattern is placed on the sand and another molding box segment is added. Additional sand is rammed over and around the pattern. Finally a cover is placed on the box and it is turned and unlatched, so that the halves of the mold may be parted and the pattern with its sprue and vent patterns removed. Additional sizing may be added and any defects introduced by the removal of the pattern are corrected. The box is closed again. This forms a "green" mold which must be dried to receive the hot metal. If the mold is not sufficiently dried a steam explosion can occur that can throw molten metal about. In some cases, the sand may be oiled instead of moistened, which makes possible casting without waiting for the sand to dry. Sand may also be bonded by chemical binders, such as furane resins or amine-hardened resins.

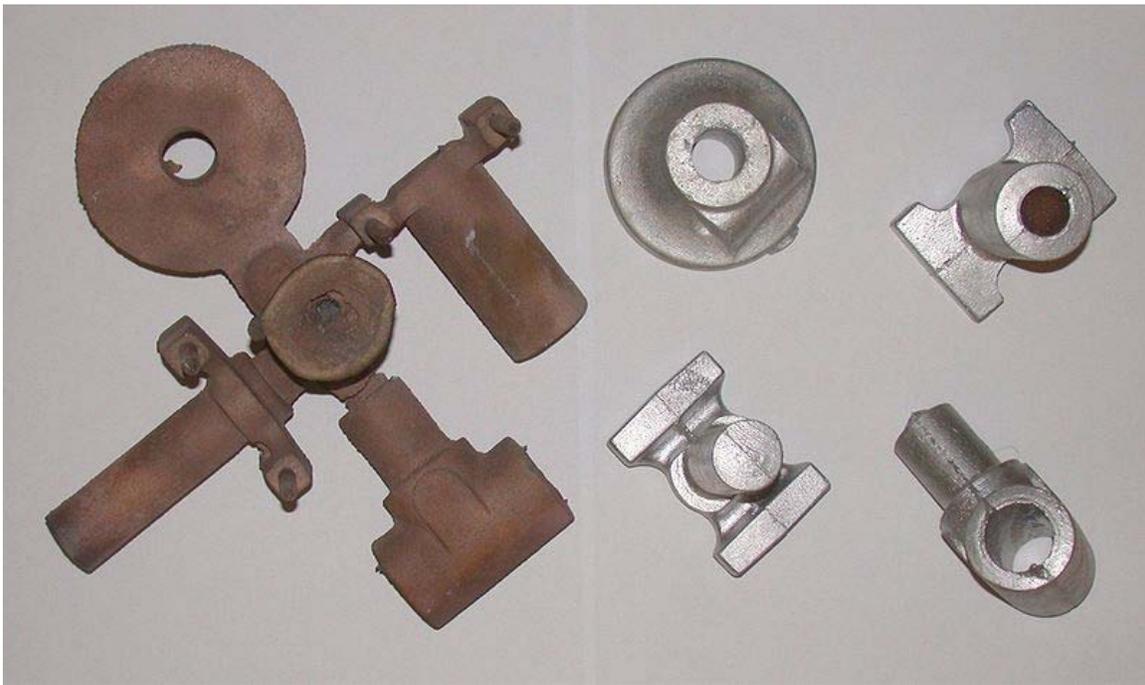
Chills

To control the solidification structure of the metal, it is possible to place metal plates, *chills*, in the mold. The associated rapid local cooling will form a finer-grained structure and may form a somewhat harder metal at these locations. In ferrous castings the effect is similar to quenching metals in forge work. The inner diameter of an engine cylinder is

made hard by a chilling core. In other metals chills may be used to promote directional solidification of the casting. In controlling the way a casting freezes it is possible to prevent internal voids or porosity inside castings.

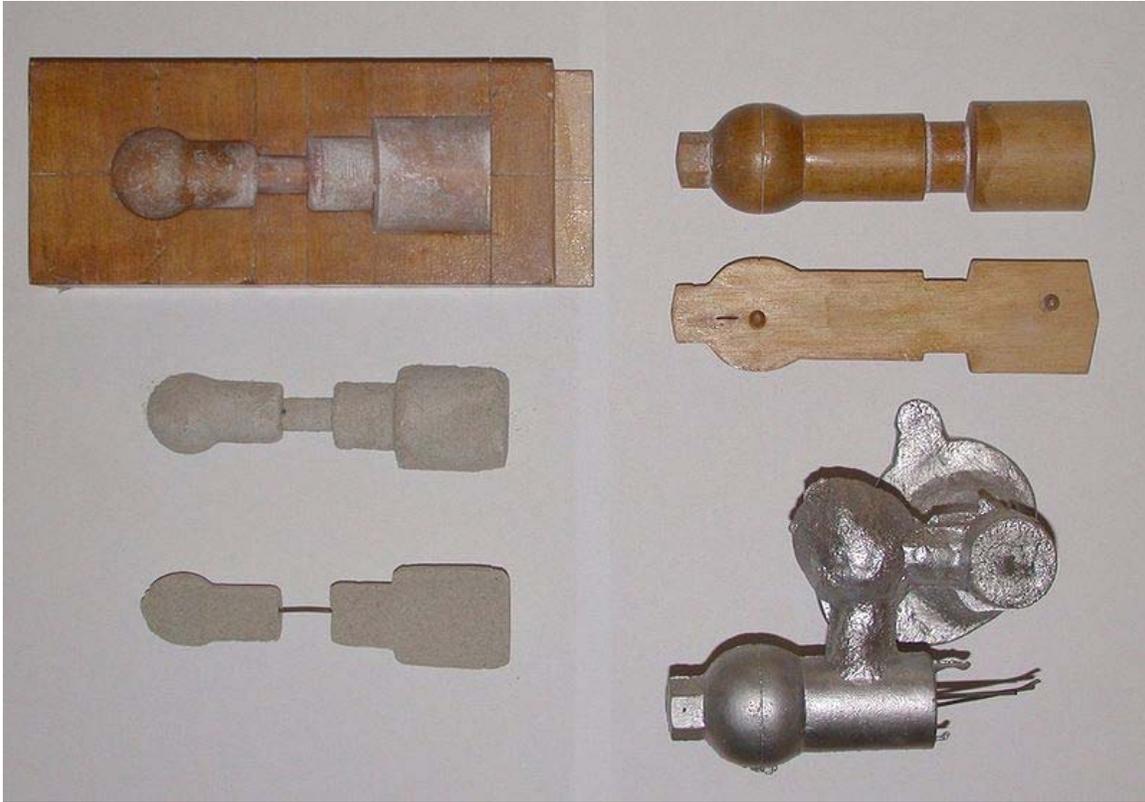
Cores

To produce cavities within the casting—such as for liquid cooling in engine blocks and cylinder heads—negative forms are used to produce *cores*. Usually sand-molded, cores are inserted into the casting box after removal of the pattern. Whenever possible, designs are made that avoid the use of cores, due to the additional set-up time and thus greater cost.



Two sets of castings (bronze and aluminium) from the above sand mold

With a completed mold at the appropriate moisture content, the box containing the sand mold is then positioned for filling with molten metal—typically iron, steel, bronze, brass, aluminium, magnesium alloys, or various pot metal alloys, which often include lead, tin, and zinc. After filling with liquid metal the box is set aside until the metal is sufficiently cool to be strong. The sand is then removed revealing a rough casting that, in the case of iron or steel, may still be glowing red. When casting with metals like iron or lead, which are significantly heavier than the casting sand, the casting flask is often covered with a heavy plate to prevent a problem known as *floating the mold*. Floating the mold occurs when the pressure of the metal pushes the sand above the mold cavity out of shape, causing the casting to fail.



Left: Corebox, with resulting (wire reinforced) cores directly below. Right:- Pattern (used with the core) and the resulting casting below (the wires are from the remains of the core)

After casting, the cores are broken up by rods or shot and removed from the casting. The metal from the sprue and risers is cut from the rough casting. Various heat treatments may be applied to relieve stresses from the initial cooling and to add hardness—in the case of steel or iron, by quenching in water or oil. The casting may be further strengthened by surface compression treatment—like shot peening—that adds resistance to tensile cracking and smooths the rough surface.

Design requirements

The part to be made and its pattern must be designed to accommodate each stage of the process, as it must be possible to remove the pattern without disturbing the molding sand and to have proper locations to receive and position the cores. A slight taper, known as draft, must be used on surfaces perpendicular to the parting line, in order to be able to remove the pattern from the mold. This requirement also applies to cores, as they must be removed from the core box in which they are formed. The sprue and risers must be arranged to allow a proper flow of metal and gasses within the mold in order to avoid an incomplete casting. Should a piece of core or mold become dislodged it may be embedded in the final casting, forming a *sand pit*, which may render the casting unusable. Gas pockets can cause internal voids. These may be immediately visible or may only be revealed after extensive machining has been performed. For critical applications, or

where the cost of wasted effort is a factor, non-destructive testing methods may be applied before further work is performed.

Processes

In general, we can distinguish between two methods of sand casting; the first one using *green sand* and the second being the *air set* method.

Green sand

These expendable molds are made of wet sands that are used to make the mold's shape. The name comes from the fact that wet sands are used in the molding process. Green sand is not green in color, but "green" in the sense that it is used in a wet state (akin to green wood). Unlike the name suggests, "green sand" is not a type of sand on its own, but is rather a mixture of:

- silica sand (SiO_2), or chromite sand (FeCr_2O), or zircon sand (ZrSiO_4), 75 to 85%
- bentonite (clay), 5 to 11%
- water, 2 to 4%
- inert sludge 3 to 5%
- anthracite (0 to 1%)

There are many recipes for the proportion of clay, but they all strike different balances between moldability, surface finish, and ability of the hot molten metal to degas. The coal, typically referred to in foundries as sea-coal, which is present at a ratio of less than 5%, partially combusts in the presence of the molten metal leading to offgassing of organic vapors.

The "air set" method

The *air set* method uses dry sand bonded with materials other than clay, using a fast curing adhesive. The latter may also be referred to as no bake mold casting. When these are used, they are collectively called "air set" sand castings to distinguish them from "green sand" castings. Two types of molding sand are natural bonded (bank sand) and synthetic (lake sand); the latter is generally preferred due to its more consistent composition.

With both methods, the sand mixture is packed around a master *pattern*, forming a mold cavity. If necessary, a temporary plug is placed in the sand and touching the pattern in order to later form a channel into which the casting fluid can be poured. Air-set molds are often formed with the help of a two-part mold having a top and bottom part, termed the cope and drag. The sand mixture is tamped down as it is added around the pattern, and the final mold assembly is sometimes vibrated to compact the sand and fill any unwanted voids in the mold. Then the pattern is removed along with the channel plug, leaving the mold cavity. The casting liquid (typically molten metal) is then poured into the mold cavity. After the metal has solidified and cooled, the casting is separated from the sand

mold. There is typically no mold release agent, and the mold is generally destroyed in the removal process.

The accuracy of the casting is limited by the type of sand and the molding process. Sand castings made from coarse green sand impart a rough texture to the surface, and this makes them easy to identify. Air-set molds can produce castings with much smoother surfaces. Surfaces can also be later ground and polished, for example when making a large bell. After molding, the casting is covered with a residue of oxides, silicates and other compounds. This residue can be removed by various means, such as grinding, or shot blasting.

During casting, some of the components of the sand mixture are lost in the thermal casting process. Green sand can be reused after adjusting its composition to replenish the lost moisture and additives. The pattern itself can be reused indefinitely to produce new sand molds. The sand molding process has been used for many centuries to produce castings manually. Since 1950, partially-automated casting processes have been developed for production lines.

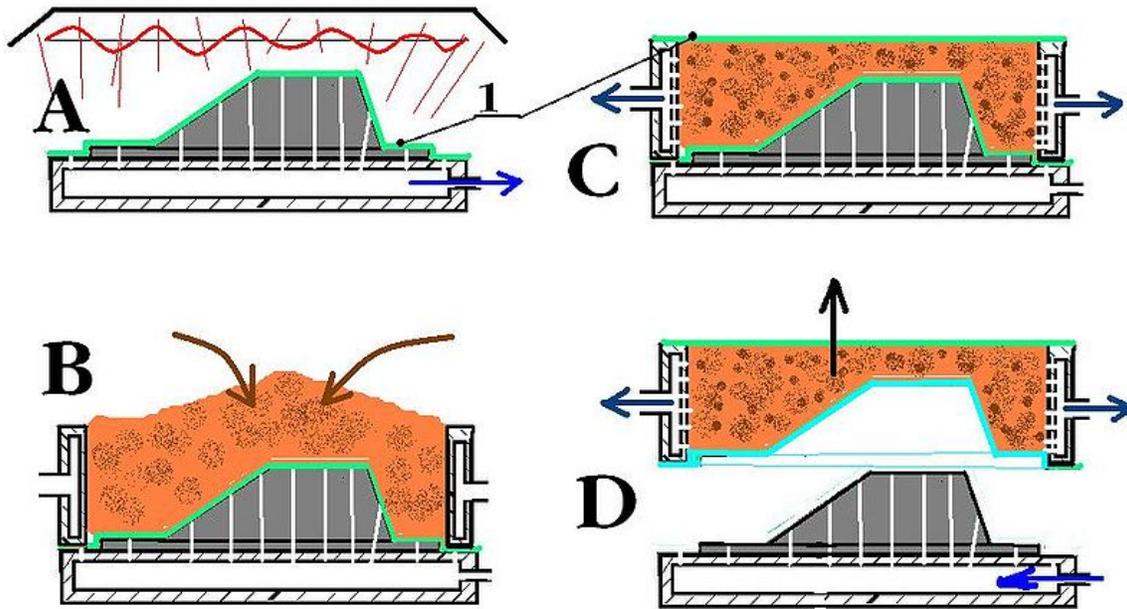
Cold box

Uses organic and inorganic binders that strengthen the mold by chemically adhering to the sand. This type of mold gets its name from not being baked in an oven like other sand mold types. This type of mold is more accurate dimensionally than green-sand molds but are more expensive.

No bake molds

No bake molds are expendable sand molds, similar to typical sand molds, except they also contain a quick-setting liquid resin and catalyst. Rather than being rammed, the molding sand is poured into the flask and held until the resin solidifies, which occurs at room temperature. This type of molding also produces a better surface finish than other types of sand molds. Because no heat is involved it is called a cold-setting process. Common flask materials that are used are wood, metal, and plastic. Common metals cast into no bake molds are brass, ferric, and aluminum alloys.

Vacuum molding



A schematic of vacuum molding

Vacuum molding (V-process) is a variation of the sand casting process for most ferrous and non-ferrous metals, in which unbonded sand is held in the flask with a vacuum. The pattern is specially vented so that a vacuum can be pulled through it. A heat-softened thin sheet (0.003 to 0.008 in (0.076 to 0.20 mm)) of plastic film is draped over the pattern and a vacuum is drawn (200 to 400 mmHg (27 to 53 kPa)). A special vacuum forming flask is placed over the plastic pattern and is filled with a free-flowing sand. The sand is vibrated to compact the sand and a sprue and pouring cup are formed in the cope. Another sheet of plastic is placed over the top of the sand in the flask and a vacuum is drawn through the special flask; this hardens and strengthens the unbonded sand. The vacuum is then released on the pattern and the cope is removed. The drag is made in the same way (without the sprue and pouring cup). Any cores are set in place and the mold is closed. The molten metal is poured while the cope and drag are still under a vacuum, because the plastic vaporizes but the vacuum keeps the shape of the sand while the metal solidifies. When the metal has solidified, the vacuum is turned off and the sand runs out freely, releasing the casting.

The V-process is known for not requiring a draft because the plastic film has a certain degree of lubricity and it expands slightly when the vacuum is drawn in the flask. The process has high dimensional accuracy, with a tolerance of ± 0.010 in for the first inch and ± 0.002 in/in thereafter. Cross-sections as small as 0.090 in (2.3 mm) are possible. The surface finish is very good, usually between 150 to 125 rms. Other advantages include no moisture related defects, no cost for binders, excellent sand permeability, and no toxic fumes from burning the binders. Finally, the pattern does not wear out because

the sand does not touch it. The main disadvantage is that the process is slower than traditional sand casting so it is only suitable for low to medium production volumes; approximately 10 to 15,000 pieces a year. However, this makes it perfect for prototype work, because the pattern can be easily modified as it is made from plastic.

DISAMATIC

Fast mold making processes

With the fast development of the car and machine building industry the casting consuming areas called for steady higher productivity. The basic process stages of the mechanical molding and casting process are similar to those described under the manual sand casting process. The technical and mental development however was so rapid and profound that the character of the sand casting process changed radically.

Mechanized sand molding

The first mechanized molding lines consisted of sand slingers and/or jolt-squeeze devices that compacted the sand in the flasks. Subsequent mold handling was mechanical using cranes, hoists and straps. After core setting the copes and drags were coupled using guide pins and clamped for closer accuracy. The molds were manually pushed off on a roller conveyor for casting and cooling.

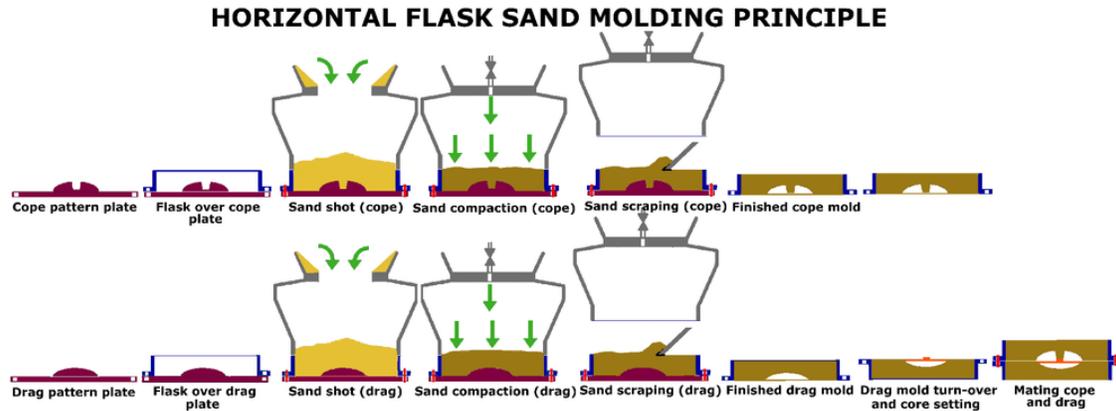
Automatic high pressure sand molding lines

Increasing quality requirements made it necessary to increase the mold stability by applying steadily higher squeeze pressure and modern compaction methods for the sand in the flasks. In early fifties the high pressure molding was developed and applied in mechanical and later automatic flask lines. The first lines were using jolting and vibrations to pre-compact the sand in the flasks and compressed air powered pistons to compact the molds.

Horizontal sand flask molding

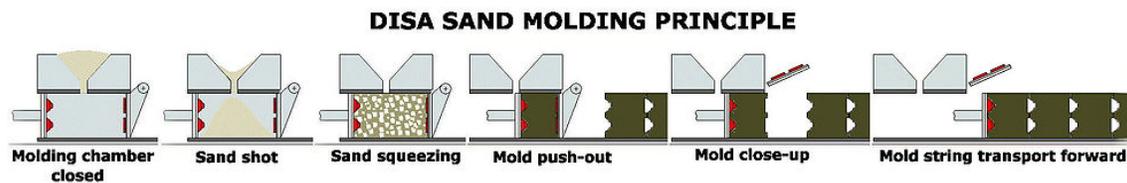
In the first automatic horizontal flask lines the sand was shot or slung down on the pattern in a flask and squeezed with hydraulic pressure of up to 140 bars. The subsequent mold handling including turn-over, assembling, pushing-out on a conveyor were accomplished either manually or automatically. In the late fifties hydraulically powered pistons or multi-piston systems were used for the sand compaction in the flasks. This method produced much more stable and accurate molds than it was possible manually or pneumatically. In the late sixties mold compaction by fast air pressure or gas pressure drop over the pre-compacted sand mold was developed (sand-impulse and gas-impact). The general working principle for most of the horizontal flask line systems is shown on the sketch below.

Today there are many manufacturers of the automatic horizontal flask molding lines. The major disadvantages of these systems is high spare parts consumption due to multitude of movable parts, need of storing, transporting and maintaining the flasks and productivity limited to approximately 90–120 molds per hour.



Vertical sand flaskless molding

In 1962, Dansk Industri Syndikat A/S (DISA) invented a flask-less molding process by using vertically parted and poured molds. The first line could produce up to 240 complete sand molds per hour. Today molding lines can achieve a molding rate of 550 sand molds per hour and requires only one monitoring operator. Maximum mismatch of two mold halves is 0.1 mm (0.0039 in).



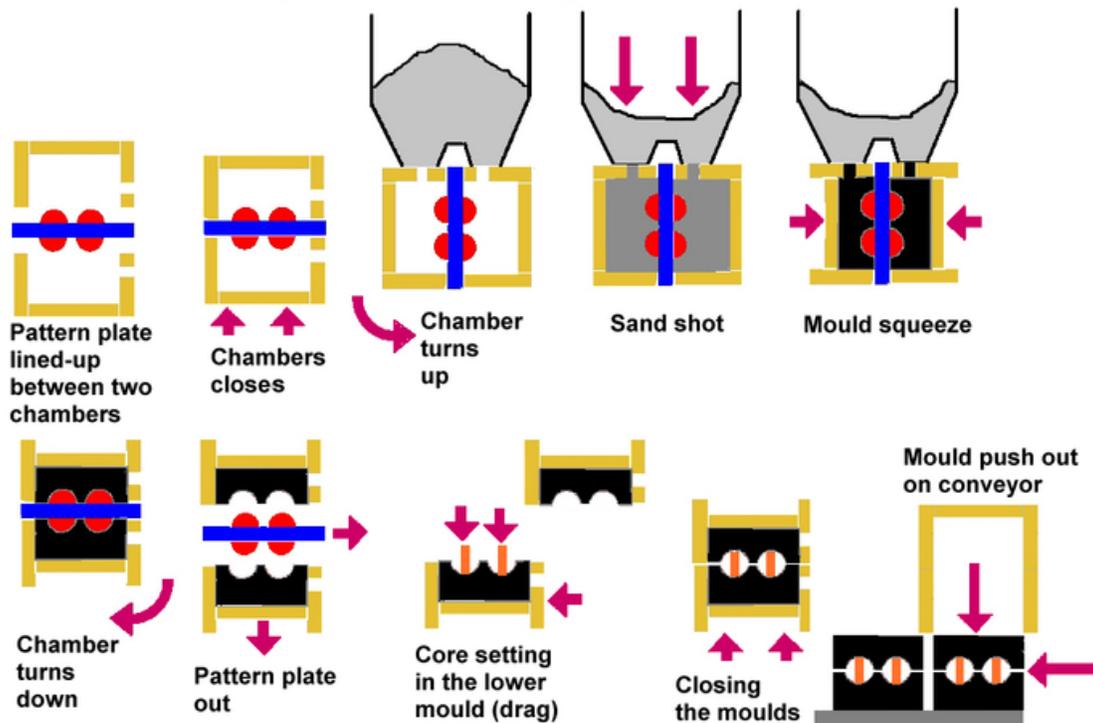
Matchplate sand molding

The principle of the matchplate, meaning pattern plates with two patterns on each side of the same plate, was developed and patented in 1910, fostering the perspectives for future sand molding improvements. However, first in the early sixties the American company Hunter Automated Machinery Corporation launched its first automatic flaskless, horizontal molding line applying the matchplate technology.

The method alike to the DISA's vertical moulding is flaskless, however horizontal. The matchplate molding technology is today used widely. Its great advantage is inexpensive pattern tooling, easiness of changing the molding tooling, thus suitability for manufacturing castings in short series so typical for the jobbing foundries. Modern matchplate molding machine is capable of high molding quality, less casting shift due to machine-mold mismatch (in some cases less than 0.15 mm (0.0059 in)), consistently

stable molds for less grinding and improved parting line definition. In addition, the machines are enclosed for a cleaner, quieter working environment with reduced operator exposure to safety risks or service-related problems.

DISAs MATCH-PLATE SAND MOULDING PRINCIPLE



Mold materials

There are four main components for making a sand casting mold: *base sand*, a *binder*, *additives*, and a *parting compound*.

Molding sands

Molding sands, also known as *foundry sands*, are defined by eight characteristics: refractoriness, chemical inertness, permeability, surface finish, cohesiveness, flowability, collapsibility, and availability/cost.

Refractoriness — This refers to the sand's ability to withstand the temperature of the liquid metal being cast without breaking down. For example some sands only need to withstand 650 °C (1,202 °F) if casting aluminum alloys, whereas steel needs a sand that will withstand 1,500 °C (2,730 °F). Sand with too low a refractoriness will melt and fuse to the casting.

Chemical inertness — The sand must not react with the metal being cast. This is especially important with highly reactive metals, such as magnesium and titanium.

Permeability — This refers to the sand's ability to exhaust gases. This is important because during the pouring process many gases are produced, such as hydrogen, nitrogen, carbon dioxide, and steam, which must leave the mold otherwise casting defects, such as blow holes and gas holes, occur in the casting. Note that for each cubic centimeter (cc) of water added to the mold 16,000 cc of steam is produced.

Surface finish — The size and shape of the sand particles defines the best surface finish achievable, with finer particles producing a better finish. However, as the particles become finer (and surface finish improves) the permeability becomes worse.

Cohesiveness (or bond) — This is the ability of the sand to retain a given shape after the pattern is removed.

Flowability – The ability for the sand to flow into intricate details and tight corners without special processes or equipment.

Collapsibility — This is the ability of the sand to be easily stripped off the casting after it has solidified. Sands with poor collapsibility will adhere strongly to the casting. When casting metals that contract a lot during cooling or with long freezing temperature ranges a sand with poor collapsibility will cause cracking and hot tears in the casting. Special additives can be used to improve collapsibility.

Availability/cost — The availability and cost of the sand is very important because for every ton (0.9 tonne) of metal poured three to six tons (2.7–5.4 tonnes) of sand is required. Moreover, most of the sand cannot be reused after it is used, because it is damaged during the casting process.

In large castings it is economical to use two different sands, because the majority of the sand will not be in contact with the casting, so it does not need any special properties. The sand that is in contact with the casting is called *facing sand*, and is designed for the casting on hand. This sand will be built up around the pattern to a thickness of 30 to 100 mm (1.2 to 3.9 in). The sand that fills in around the facing sand is called *backing sand*. This sand is simply silica sand with only a small amount of binder and no special additives.

Types of base sands

Base sand is the type used to make the mold or core without any binder. Because it does not have a binder it will not bond together and is not usable in this state.

Silica sand

Silica (SiO₂) sand is the stereotype sand (i.e. the sand found on a beach) and is also the most commonly used sand. It is made by either crushing sandstone or taken from natural occurring locations, such as beaches and river beds. The fusion point of pure silica is 1,760 °C (3,200 °F), however the sands used have a lower melting point due to

impurities. For high melting point casting, such as steels, a minimum of 98% pure silica sand must be used; however for lower melting point metals, such as cast iron and non-ferrous metals, a lower purity sand can be used (between 94 and 98% pure).

Silica sand is the most commonly used sand because of its great abundance, and, thus, low cost (therein being its greatest advantage). Its disadvantages are high thermal expansion, which can cause casting defects with high melting point metals, and low thermal conductivity, which can lead to unsound casting. It also cannot be used with certain basic metal because it will chemically interact with the metal forming surface defect. Finally, it causes silicosis in foundry workers.

Olivine sand

Olivine is a mixture of orthosilicates of iron and magnesium from the mineral dunite. Its main advantage is that it is free from silica, therefore it can be used with basic metals, such as manganese steels. Other advantages include a low thermal expansion, high thermal conductivity, and high fusion point. Finally, it is safer to use than silica, therefore it is popular in Europe.

Chromite sand

Chromite sand is a solid solution of spinels. Its advantages are a low percentage of silica, a very high fusion point (1,850 °C (3,360 °F)), and a very high thermal conductivity. Its disadvantage is its costliness, therefore its only used with expensive alloy steel casting and to make cores.

Zircon sand

Zircon sand is a compound of approximately two-thirds zircon oxide (Zr_2O) and one-third silica. It has the highest fusion point of all the base sands at 2,600 °C (4,710 °F), a very low thermal expansion, and a high thermal conductivity. Because of these good properties it is commonly used when casting alloy steels and other expensive alloys. It is also used as a mold wash (a coating applied to the molding cavity) to improve surface finish. However, it is expensive and not readily available.

Chamotte sand

Chamotte is made by calcining fire clay ($Al_2O_3-SiO_2$) above 1,100 °C (2,010 °F). Its fusion point is 1,750 °C (3,180 °F) and has low thermal expansion. It is the second cheapest sand, however it is still twice as expensive as silica. Its disadvantages are very coarse grains, which result in a poor surface finish, and it is limited to dry sand molding. Mold washes are used to overcome the surface finish problem. This sand is usually used when casting large steel workpieces.

Other materials

Modern casting production methods can manufacture thin and accurate molds—of a material superficially resembling papier-mâché, such as is used in egg cartons, but that is refractory in nature—that are then supported by some means, such as dry sand surrounded by a box, during the casting process. Due to the higher accuracy it is possible to make thinner and hence lighter castings, because extra metal need not be present to allow for variations in the molds. These thin-mold casting methods have been used since the 1960s in the manufacture of cast-iron engine blocks and cylinder heads for automotive applications.

Binders

Binders are added to a base sand to bond the sand particles together (i.e. it is the glue that holds the mold together).

Clay and water

A mixture of clay and water is the most commonly used binder. There are two types of clay commonly used: bentonite and kaolinite, with the former being the most common.

Oil

Oils, such as linseed oil, other vegetable oils and marine oils, used to be used as a binder, however due to their increasing cost, they have been mostly phased out. The oil also required careful baking at 100 to 200 °C (212 to 392 °F) to cure (if overheated the oil becomes brittle, wasting the mold).

Resin

Resin binders are natural or synthetic high melting point gums. The two common types used are urea formaldehyde (UF) and phenol formaldehyde (PF) resins. PF resins have a higher heat resistance than UF resins and cost less. There are also cold-set resins, which use a catalyst instead of a heat to cure the binder. Resin binders are quite popular because different properties can be achieved by mixing with various additives. Other advantages include good collapsibility, low gassing, and they leave a good surface finish on the casting.

Sodium silicate

Sodium silicate [Na_2SiO_3 or $(\text{Na}_2\text{O})(\text{SiO}_2)$] is a high strength binder used with silica molding sand. To cure the binder carbon dioxide gas is used, which creates the following reaction:



The advantage to this binder is that it occurs at room temperature and quickly. The disadvantage is that its high strength leads to shakeout difficulties and possibly hot tears in the casting.

Additives

Additives are added to the molding components to improve: surface finish, dry strength, refractoriness, and "cushioning properties".

Up to 5% of *reducing agents*, such as coal powder, pitch, creosote, and fuel oil, may be added to the molding material to prevent wetting (prevention of liquid metal sticking to sand particles, thus leaving them on the casting surface), improve surface finish, decrease metal penetration, and burn-on defects. These additives achieve this by creating gases at the surface of the mold cavity, which prevent the liquid metal from adhering to the sand. Reducing agents are not used with steel casting, because they can carburize the metal during casting.

Up to 3% of "cushioning material", such as wood flour, saw dust, powdered husks, peat, and straw, can be added to reduce scabbing, hot tear, and hot crack casting defects when casting high temperature metals. These materials are beneficial because burn-off when the metal is poured creating voids in the mold, which allow it to expand. They also increase collapsibility and reduce shakeout time.

Up to 2% of *cereal binders*, such as dextrin, starch, sulphite lye, and molasses, can be used to increase dry strength (the strength of the mold after curing) and improve surface finish. Cereal binders also improve collapsibility and reduce shakeout time because they burn-off when the metal is poured. The disadvantage to cereal binders is that they are expensive.

Up to 2% of iron oxide powder can be used to prevent mold cracking and metal penetration, essentially improving refractoriness. Silica flour (fine silica) and zircon flour also improve refractoriness, especially in ferrous castings. The disadvantages to these additives is that they greatly reduce permeability.

Parting compounds

To get the pattern out of the mold, prior to casting, a parting compound is applied to the pattern to ease removal. They can be a liquid or a fine powder (particle diameters between 75 and 150 micrometres (0.0030 and 0.0059 in)). Common powders include talc, graphite, and dry silica; common liquids include mineral oil and water-based silicon solutions. The latter are more commonly used with metal and large wooden patterns.

History

In 1924, the Ford automobile company set a record by producing 1 million cars, in the process consuming one-third of the total casting production in the U.S. As the automobile

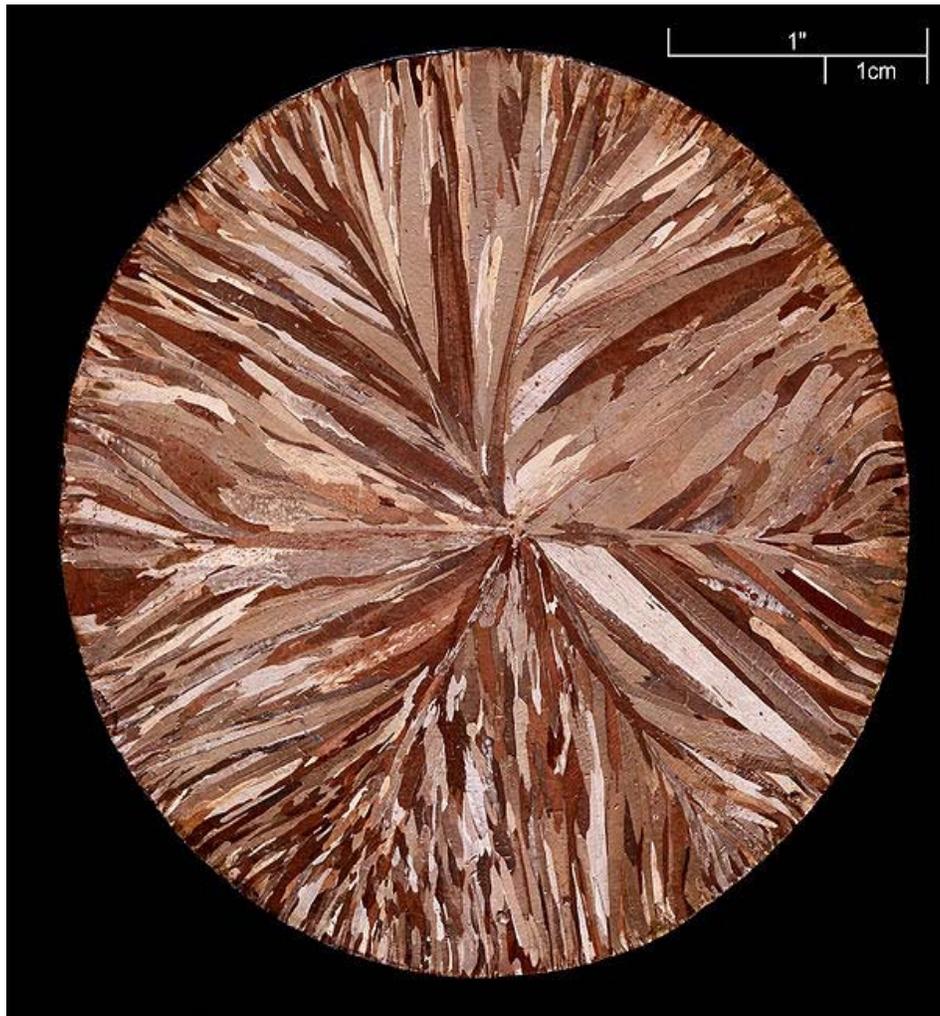
industry grew the need for increased casting efficiency grew. The increasing demand for castings in the growing car and machine building industry during and after World War I and World War II, stimulated new inventions in mechanization and later automation of the sand casting process technology.

There was not one bottleneck to faster casting production but rather several. Improvements were made in molding speed, molding sand preparation, sand mixing, core manufacturing processes, and the slow metal melting rate in cupola furnaces. In 1912, the sand slinger was invented by the American company Birdsley & Piper. In 1912, the first sand mixer with individually mounted revolving plows was marketed by the Simpson Company. In 1915, the first experiments started with bentonite clay instead of simple fire clay as the bonding additive to the molding sand. This increased tremendously the green and dry strength of the molds. In 1918, the first fully automated foundry for fabricating hand grenades for the U.S. Army went into production. In the 1930s the first high-frequency coreless electric furnace was installed in the U.S. In 1943, ductile iron was invented by adding magnesium to the widely used grey iron. In 1940, thermal sand reclamation was applied for molding and core sands. In 1952, the "D-process" was developed for making shell molds with fine, pre-coated sand. In 1953, the hotbox core sand process in which the cores are thermally cured was invented. In 1954, a new core binder - water glass hardened with CO₂ from the ambient air, was applied.

Chapter-14

Continuous Casting & Lost-Foam Casting

Continuous Casting

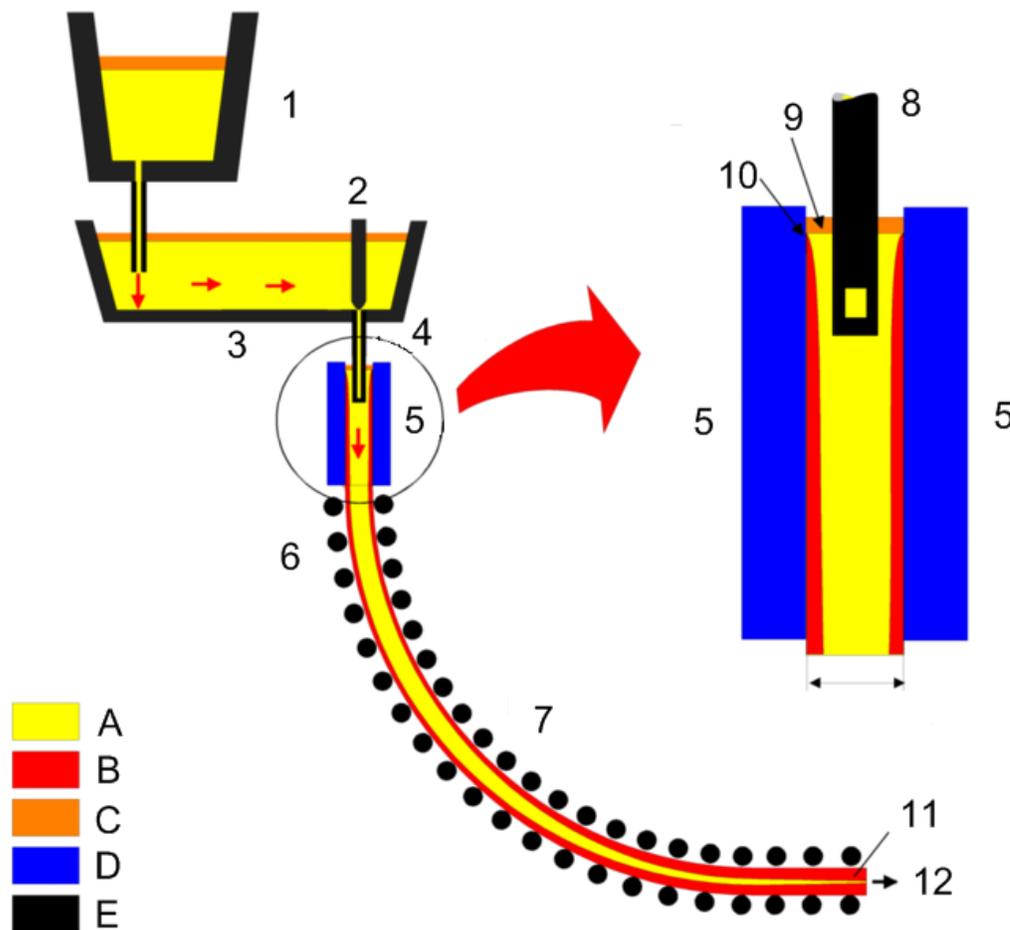


The macrostructure of continuously cast copper (99.95% pure), etched, $\varnothing \approx 83$ mm.

Continuous casting, also called **strand casting**, is the process whereby molten metal is solidified into a "semifinished" billet, bloom, or slab for subsequent rolling in the finishing mills. Prior to the introduction of continuous casting in the 1950s, steel was poured into stationary molds to form ingots. Since then, "continuous casting" has evolved to achieve improved yield, quality, productivity and cost efficiency. It allows lower-cost production of metal sections with better quality, due to the inherently lower costs of continuous, standardised production of a product, as well as providing increased control over the process through automation. This process is used most frequently to cast steel (in terms of tonnage cast). Aluminium and copper are also continuously cast.

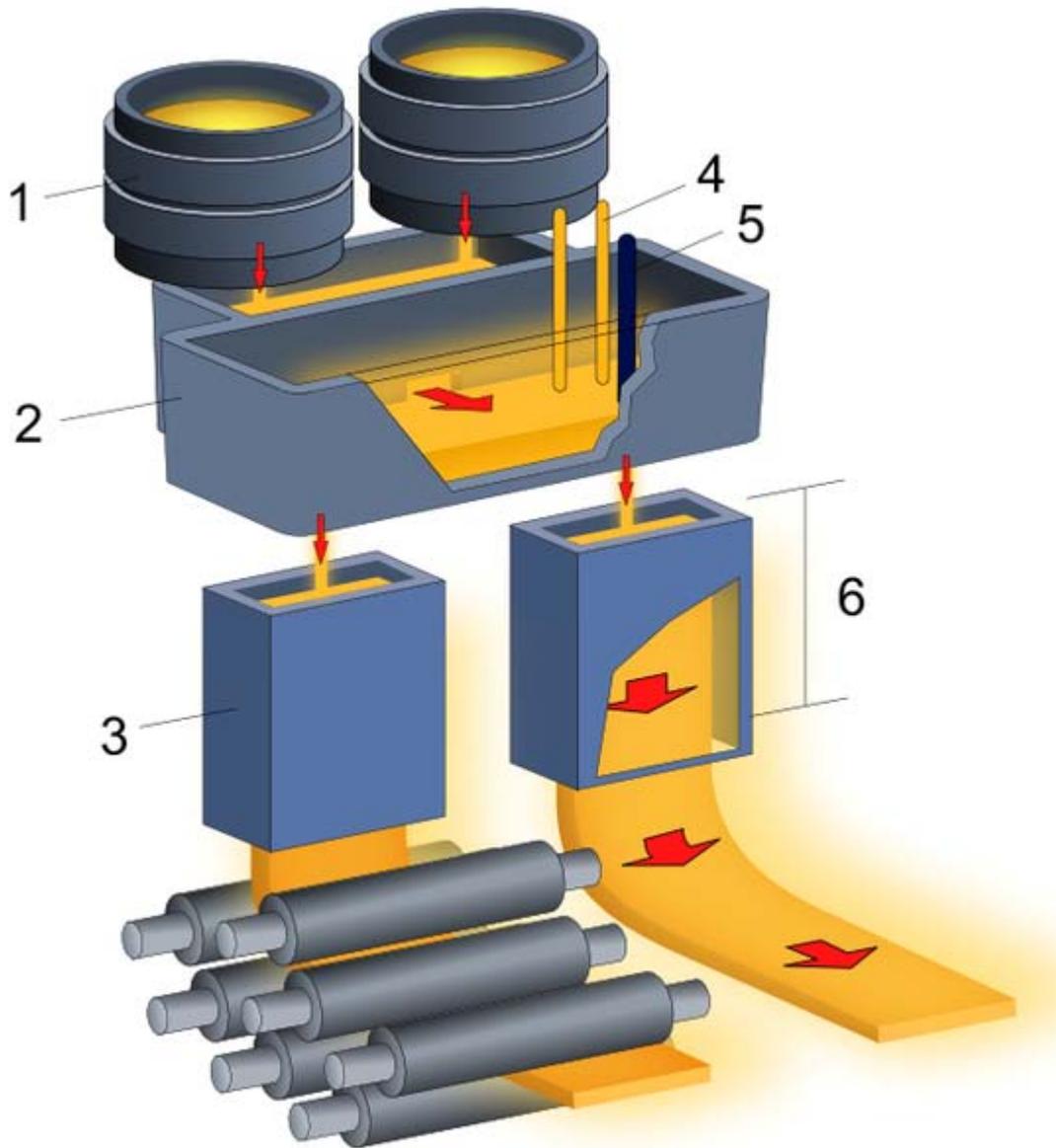
Sir Henry Bessemer, of Bessemer converter fame, received a patent in 1857 for casting metal between two contra-rotating rollers. The basic outline of this system has recently been implemented today in the casting of steel strip.

Equipment and process



1. Ladle 2. Stopper 3. Tundish 4. Shroud 5. Mold 6. Roll support 7. Turning zone 8. Shroud 9. Bath level 10. Meniscus 11. Withdrawal unit 12. Slab

A. Liquid metal B. Solidified metal C. Slag D. Water-cooled copper plates E. Refractory material



A 3D schematic

Molten metal (known as *hot metal* in industry) is tapped into the ladle from furnaces. After undergoing any ladle treatments, such as alloying and degassing, and arriving at the correct temperature, the ladle is transported to the top of the casting machine. Usually, the ladle sits in a slot on a rotating turret at the casting machine; one ladle is 'on cast' (feeding the casting machine) while the other is made ready, and is switched to the casting position once the first ladle is empty.

From the ladle, the hot metal is transferred via a refractory shroud (pipe) to a holding bath called a tundish. The tundish allows a reservoir of metal to feed the casting machine

while ladles are switched, thus acting as a buffer of hot metal, as well as smoothing out flow, regulating metal feed to the molds and cleaning the metal.

Metal is drained from the tundish through another shroud into the top of an open-base copper mold. The depth of the mold can range from 0.5 to 2 metres (20 to 79 in), depending on the casting speed and section size. The mold is water-cooled to solidify the hot metal directly in contact with it; this is the *primary cooling* process. It also oscillates vertically (or in a near vertical curved path) to prevent the metal sticking to the mold walls. A lubricant can also be added to the metal in the mold to prevent sticking, and to trap any slag particles—including oxide particles or scale—that may still be present in the metal and bring them to the top of the pool to form a floating layer of slag. Often, the shroud is set so the hot metal exits it below the surface of the slag layer in the mold and is thus called a submerged entry nozzle (SEN). In some cases, shrouds may not be used between tundish and mold; in this case, interchangeable metering nozzles in the base of the tundish direct the metal into the moulds. Some continuous casting layouts feed several molds from the same tundish.

In the mold, a thin shell of metal next to the mold walls solidifies before the middle section, now called a strand, exits the base of the mold into a spray-chamber; the bulk of metal within the walls of the strand is still molten. The strand is immediately supported by closely spaced, water cooled rollers; these act to support the walls of the strand against the ferrostatic pressure (compare hydrostatic pressure) of the still-solidifying liquid within the strand. To increase the rate of solidification, the strand is also sprayed with large amounts of water as it passes through the spray-chamber; this is the *secondary cooling* process. Final solidification of the strand may take place after the strand has exited the spray-chamber.

It is here that the design of continuous casting machines may vary. This describes a 'curved apron' casting machine; vertical configurations are also used. In a curved apron casting machine, the strand exits the mold vertically (or on a near vertical curved path) and as it travels through the spray-chamber, the rollers gradually curve the strand towards the horizontal. In a vertical casting machine, the strand stays vertical as it passes through the spray-chamber. Molds in a curved apron casting machine can be straight or curved, depending on the basic design of the machine.

In a true "Horizontal Casting Machine", the mold axis is horizontal and the flow of steel is horizontal from liquid to thin shell to solid (no bending). In this type of machine, either strand oscillation or mold oscillation is used to prevent sticking in the mold.

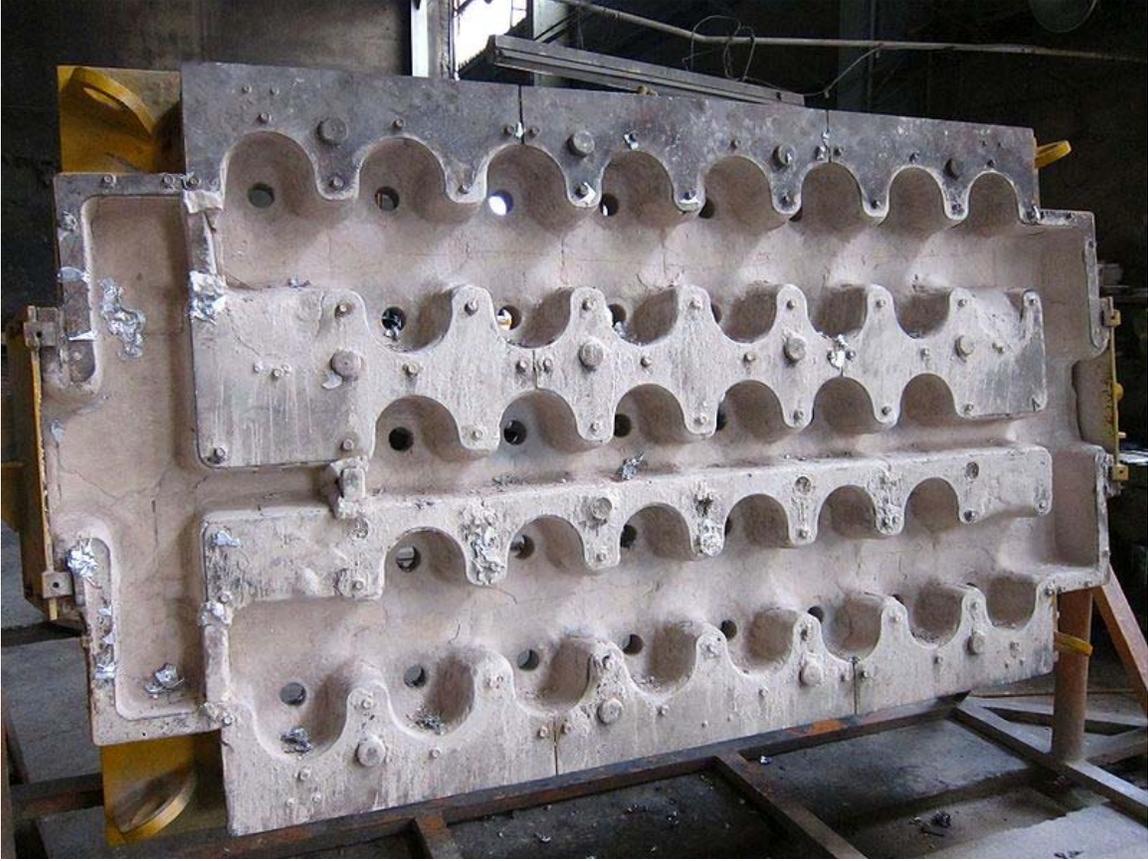
After exiting the spray-chamber, the strand passes through straightening rolls (if cast on other than a vertical machine) and withdrawal rolls. There may be a hot rolling stand after withdrawal, in order to take advantage of the metal's hot condition to pre-shape the final strand. Finally, the strand is cut into predetermined lengths by mechanical shears or by travelling oxyacetylene torches, is marked for identification and either taken to a stockpile or the next forming process.

In many cases the strand may continue through additional rollers and other mechanisms which might flatten, roll or extrude the metal into its final shape.

Casting machines for aluminium and copper



continuous hot vertical casting in process (aluminum)



molten aluminum pours into this casting die (top view of die)



bottom end of casting die



the resulting Aluminum blanks (after cutting to size)

Aluminium and copper can be cast horizontally and can be more easily cast into near net shape, especially strip, due to their lower melting temperatures.

Range of continuously cast sections

- Casting machines are designated to be billet, bloom or slab casters.
- Slab casters tend to cast sections with an aspect ratio that is much wider than it is thick:
 - Conventional slabs lie in the range 100–1600 mm wide by 180–250 mm thick and up to 12 m long with conventional casting speeds of up to 1.4 m/minute, (however slab widths and casting speeds are currently increasing).
 - Wider slabs are available up to 3250×150 mm, for example at Nanjing Iron & Steel in China.
 - Thick slabs are available up to 2400×400 mm, for example at Shougang Shouqin in Qinhuangdao, China.
 - Thin slabs: 1680×50 mm
- Conventional bloom casters cast sections above 200×200 mm e.g. the Aldwarke Bloom caster in Rotherham, UK, casts sections of 560×400 mm. The bloom length can vary from 4 to 10 m

- Billet casters cast smaller section sizes, such as below 200 mm square, with lengths up to 12 m long. Cast speeds can reach up to 4 m/minute.
- Rounds: either 500 mm or 140 mm in diameter
- Conventional beam blanks: look similar to I-beams in cross-section; 1048×450 mm or 438×381 mm overall
- Near net shape beam blanks: 850×250 mm overall
- Strip: 2–5 mm thick by 760–1330 mm wide

Startup, control of the process and problems

Starting a continuous casting machine involves placing a dummy bar (essentially a curved metal beam) up through the spray chamber to close off the base of the mould. Metal is poured into the mould and withdrawn with the dummy bar once it solidifies. It is extremely important that the metal supply afterwards be guaranteed to avoid unnecessary shutdowns and restarts, known as 'turnarounds'. Each time the caster stops and restarts, a new tundish is required, as any uncast metal in the tundish cannot be drained and instead freezes into a 'skull'. Avoiding turnarounds requires the meltshop, including ladle furnaces (if any) to keep tight control on the temperature of the metal, which can vary dramatically with alloying additions, slag cover and deslagging, and the preheating of the ladle before it accepts metal, among other parameters. However, the cast rate may be lowered by reducing the amount of metal in the tundish (although this can increase wear on the tundish), or if the caster has multiple strands, one or more strands may be shut down to accommodate upstream delays. Turnarounds may be scheduled into a production sequence if the tundish temperature becomes too high after a certain number of heats.

Many continuous casting operations are now fully computer-controlled. Several electromagnetic and thermal sensors in the ladle shroud, tundish and mould sense the metal level or weight, flow rate and temperature of the hot metal, and the programmable logic controller (PLC) can set the rate of strand withdrawal via speed control of the withdrawal rolls. The flow of metal into the moulds can be controlled via two methods:

- By slide gates or stopper rods at the top of the mould shrouds
- If the metal is open-poured, then the metal flow into the moulds is controlled solely by the internal diameter of the metering nozzles. These nozzles are usually interchangeable.

Overall casting speed can be adjusted by altering the amount of metal in the tundish, via the ladle slide gate. The PLC can also set the mould oscillation rate and the rate of mould powder feed, as well as the spray water flow. Computer control also allows vital casting data to be repeated to other manufacturing centres (particularly the steelmaking furnaces), allowing their work rates to be adjusted to avoid 'overflow' or 'underrun' of product.

While the large amount of automation helps produce castings with no shrinkage and little segregation, continuous casting is of no use if the metal is not clean beforehand, or becomes 'dirty' during the casting process. One of the main methods through which hot metal may become dirty is by oxidation, which occurs rapidly at molten metal

temperatures (up to 1700 °C); inclusions of gas, slag or undissolved alloys may also be present. To prevent oxidation, the metal is isolated from the atmosphere as much as possible. To achieve this, exposed metal surfaces are covered – by the shrouds, or in the case of the ladle, tundish and mould, by synthetic slag. In the tundish, any inclusions – gas bubbles, other slag or oxides, or undissolved alloys – may also be trapped in the slag layer.

A major problem that may occur in continuous casting is *breakout*. This is when the thin shell of the strand breaks, allowing the still-molten metal inside the strand to spill out and foul the machine, requiring a turnaround. Often, breakout is due to too high a withdrawal rate, as the shell has not had the time to solidify to the required thickness, or the metal is too hot, which means that final solidification takes place well below the straightening rolls and the strand breaks due to stresses applied during straightening. A breakout can also occur if solidifying steel sticks to the mould surface, causing a tear in the shell of the strand. If the incoming metal is overheated, it is preferable to stop the caster than to risk a breakout. Additionally, lead contamination of the metal (caused by counterweights or lead-acid batteries in the initial steel charge) can form a thin film between the mould wall and the steel, inhibiting heat removal and shell growth and increasing the risk of breakouts.

Another problem that may occur is a *carbon boil* – oxygen dissolved in the steel reacts with also-present carbon to generate bubbles of carbon monoxide. As the term *boil* suggests, this reaction is extremely fast and violent, generating large amounts of hot gas, and is especially dangerous if it occurs in the confined spaces of a casting machine. Oxygen can be removed through the addition of silicon or aluminium to the steel, which reacts to form silicon oxide (silica) or aluminium oxide (alumina). However, too much alumina in the steel will clog the casting nozzles and cause the steel to 'choke off'.

Computational fluid dynamics and other fluid flow techniques are being used extensively in the design of new continuous casting operations, especially in the tundish, to ensure that inclusions and turbulence are removed from the hot metal, yet ensure that all the metal reaches the mould before it cools too much. Slight adjustments to the flow conditions within the tundish or the mould can mean the difference between high and low rejection rates of the product.

Starter bar

The starter bar has a free end portion which is flexible for storage and a substantially rigid portion at the end which plugs the mold. The starter bar is constructed in discrete blocks secured to one side of a planar spine provided in segments and arranged end to end. Adjustable spacers in the form of tapered blocks are disposed between the blocks of the bar to allow the starter bar to be self-supporting in a curved configuration corresponding to the casting path. A more flexible spine in the end portion of the starter bar allows the starter bar to be curved to a tighter radius than that of the casting path while the blocks fan out in an unsupported configuration. A storage ramp is provided to support the flexible end in the stored position.

Direct strip casting

Direct strip casting is a continuous casting process for producing metallic sheet directly from the molten state that minimises the need for substantial secondary processing.

Lost-Foam Casting

Lost-foam casting (LFC) is a type of evaporative-pattern casting process that is similar to investment casting except foam is used for the pattern instead of wax. This process takes advantage of the low boiling point of foam to simplify the investment casting process by removing the need to melt the wax out of the mold.

Process

First, a pattern is made from polystyrene foam, which can be done many different ways. For small volume runs the pattern can be hand cut or machined from a solid block of foam; if the geometry is simple enough it can even be cut using a hot-wire foam cutter. If the volume is large, then the pattern can be mass-produced by a process similar to injection molding. Pre-expanded beads of polystyrene are injected into a preheated aluminum mold at low pressure. Steam is then applied to the polystyrene which causes it to expand more to fill the die. The final pattern is approximately 97.5% air and 2.5% polystyrene. Pre-made pouring basins, runners, and risers can be hot glued to the pattern to finish it.

Next, the foam cluster is coated with ceramic investment, also known as the refractory coating, via dipping, brushing, spraying or flow coating. This coating creates a barrier between the smooth foam surface and the coarse sand surface. Secondly it controls permeability, which allows the gas created by the vaporized foam pattern to escape through the coating and into the sand. Controlling permeability is a crucial step to avoid sand erosion. Finally, it forms a barrier so that molten metal does not penetrate or cause sand erosion during pouring. After the coating dries, the cluster is placed into a flask and backed up with un-bonded sand. The sand is then compacted using a vibration table. Once compacted, the mold is ready to be poured. Automatic pouring is commonly used in LFC, as the pouring process is significantly more critical than in conventional foundry practice.

Details

Commonly cast metals include cast irons, aluminium alloys, steels, and nickel alloys; less frequently stainless steels and copper alloys are also cast. The size range is from 0.5 kg (1.1 lb) to several tonnes (tons). The minimum wall thickness is 2.5 mm (0.098 in) and there is no upper limit. Typical surface finishes are from 2.5 to 25 μm (100 to 1000 μin) RMS. Typical linear tolerances are ± 0.005 mm/mm (0.005 in/in).

Advantages and disadvantages

This casting process is advantageous for very complex castings that would regularly require cores. It is also dimensionally accurate, maintains an excellent surface finish, requires no draft, and has no parting lines so no flash is formed. As compared to investment casting, it is cheaper because it is a simpler process and the foam is cheaper than the wax. Risers are not usually required due to the nature of the process; because the molten metal vaporizes the foam the first metal into the mold cools more quickly than the rest, which results in natural directional solidification. Foam is easy to manipulate, carve and glue, due to its unique properties. The flexibility of LFC often allows for consolidating the parts into one integral component; other forming processes would require the production of one or more parts to be assembled.

The two main disadvantages are that pattern costs can be high for low volume applications and the patterns are easily damaged or distorted due to their low strength. If a die is used to create the patterns there is a large initial cost.

History

Lost-foam casting was invented in 1964 by M.C. Flemmings. Public recognition of the benefits of LFC was made by General Motors in the mid 1980s when it announced its new car line, Saturn, would utilize LFC for production of all engine blocks, cylinder heads, crankshafts, differential carriers, and transmission cases.

Chapter-15

Plaster Mold Casting & Shell Molding

Plaster Mold Casting

Plaster mold casting is a metalworking casting process similar to sand casting except the molding material is plaster of paris instead of sand. Like sand casting, plaster mold casting is an expendable mold processes, however it can only be used with non-ferrous materials. It is used for castings as small as 30 g (1 oz) to as large as 45 kg (99 lb). Generally, the form takes less than a week to prepare, after which a production rate of 1–10 units/hr-mold is achieved.

Parts that are typically made by plaster casting are lock components, gears, valves, fittings, tooling, and ornaments.

Details

The plaster is not pure plaster of paris, but rather has additives to improve green strength, dry strength, permeability, and castability. For instance, talc or magnesium oxide are added to prevent cracking and reduce setting time; lime and cement limit expansion during baking; glass fibers increase strength; sand can be used as a filler. The ratio of ingredients is 70–80% gypsum and 20–30% additives.

The pattern is usually made from metal, however rubber molds may be used for complex geometry; these molds are called Rubber plaster molds. For example, if the casting includes reentrant angles or complex angular surfaces then the rubber is flexible enough to be removed, unlike metal. These molds are also inexpensive, reusable, more accurate than steel molds, fast to produce, and easy to change.

Typical tolerances are 0.1 mm (0.0039 in) for the first 50 mm (2.0 in) and 0.02 mm per additional centimeter (0.002 in per additional inch). A draft of 0.5 to 1 degree is required. Standard surface finishes that are attainable are 1.3 to 4 micrometres (50–125 μin).

Process

First, the plaster is mixed and the pattern is sprayed with a thin film of parting compound to prevent the plaster from sticking to the pattern. The plaster is then poured over the pattern and the unit shaken so that the plaster fills any small features. The plaster sets, usually in about 15 minutes, and the pattern is removed. The mold is then baked, between 120 °C (248 °F) and 260 °C (500 °F), to remove any excess water. The dried mold is then assembled, preheated, and the metal poured. Finally, after the metal has solidified, the plaster is broken from the cast part. The used plaster cannot be reused.

Advantages & disadvantages

Plaster mold casting is used when an excellent surface finish and good dimensional accuracy is required. Because the plaster has a low thermal conductivity and heat capacity the metal cools more slowly than in a sand mold, which allows the metal to fill thin cross-sections; the minimum possible cross-section is 0.6 mm (0.024 in). This results in a near net shape casting, which can be a cost advantage on complex parts. It also produces minimal scrap material.

The major disadvantage of the process is that it can only be used with lower melting temperature non-ferrous materials, such as aluminium, copper, magnesium, and zinc. The most commonly used materials are aluminium and copper. The maximum working temperature of plaster is 1,200 °F (649 °C), so higher melting temperature materials would melt the plaster mold. Also, the sulfur in the gypsum reacts with iron, making it unsuitable for casting ferrous materials.

Another disadvantage is that its long cooling times restrict production volume.

Plaster is not as stable as sand, so it is dependent on several factors, including the consistency of the plaster composition, pouring procedures, and curing techniques. If these factors are not closely monitored the mold can be distorted, shrink upon drying, have a poor surface finish, or fail completely.

Shell Molding

Shell molding, also known as **shell-mold casting**, is an expendable mold casting process that uses a resin covered sand to form the mold. As compared to sand casting, this process has better dimensional accuracy, a higher productivity rate, and lower labor requirements. It is used for small to medium parts that require high precision.

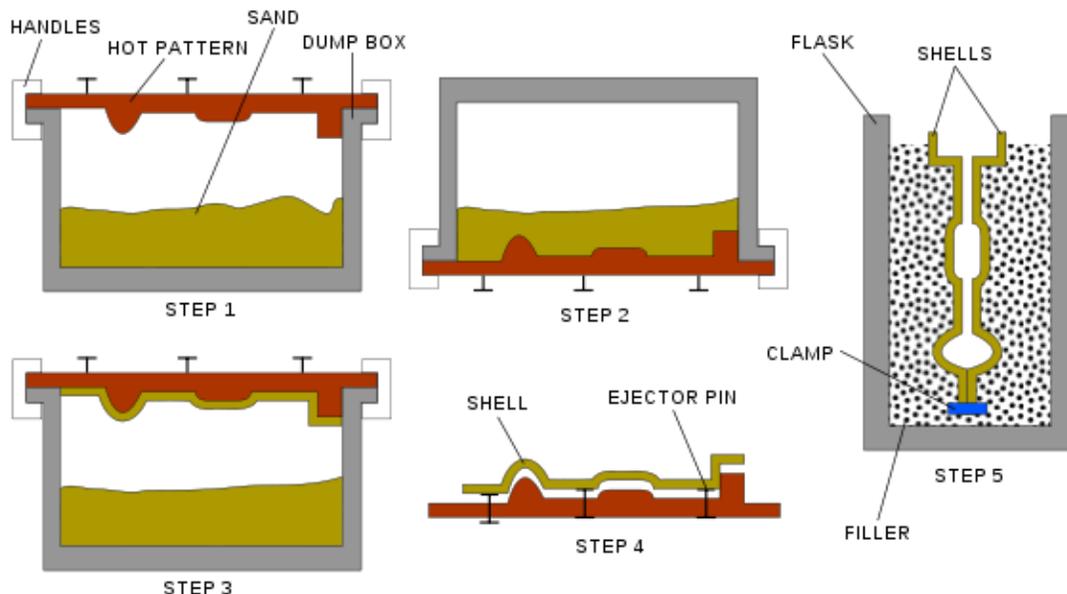
Examples of shell molded items include gear housings, cylinder heads and connecting rods. It is also used to make high-precision molding cores.

Process

The process of creating a shell mold consists of six steps:

1. Fine silica sand that is covered in a thin (3–6%) thermosetting phenolic resin and liquid catalyst is dumped, blown, or shot onto a hot pattern. The pattern is usually made from cast iron and is heated to 230 to 315 °C (450 to 600 °F). The sand is allowed to sit on the pattern for a few minutes to allow the sand to partially cure.
2. The pattern and sand are then inverted so the excess sand drops free of the pattern, leaving just the "shell". Depending on the time and temperature of the pattern the thickness of the shell is 10 to 20 mm (0.4 to 0.8 in).
3. The pattern and shell together are placed in an oven to finish curing the sand. The shell now has a tensile strength of 350 to 450 psi (2.4 to 3.1 MPa).
4. The hardened shell is then stripped from the pattern.
5. Two or more shells are then combined, via clamping or gluing using a thermoset adhesive, to form a mold. This finished mold can then be used immediately or stored almost indefinitely.
6. For casting the shell mold is placed inside a flask and surrounded with shot, sand, or gravel to reinforce the shell.

The machine that is used for this process is called a *shell molding machine*. It heats the pattern, applies the sand mixture, and bakes the shell.



Details

Setup and production of shell mold patterns takes weeks, after which an output of 5–50 pieces/hr-mold is attainable. Common materials include cast iron, aluminum and copper alloys. Aluminum and magnesium products average about 13.5 kg (30 lb) as a

normal limit, but it is possible to cast items in the 45–90 kg (100–200 lb) range. The small end of the limit is 30 g (1 oz). Depending on the material, the thinnest cross-section castable is 1.5 to 6 mm (0.06 to 0.24 in). The minimum draft is 0.25 to 0.5 degrees.

Typical tolerances are 0.005 mm/mm or in/in because the sand compound is designed to barely shrink and a metal pattern is used. The cast surface finish is 0.3–4.0 micrometers (50–150 μin) because a finer sand is used. The resin also assists in forming a very smooth surface. The process, in general, produces very consistent castings from one casting to the next.

The sand-resin mix can be recycled by burning off the resin at high temperatures.

Advantages and disadvantages

One of the greatest advantages of this process is that it can be completely automated for mass production. The high productivity, low labor costs, good surface finishes, and precision of the process can more than pay for itself if it reduces machining costs. There are also few problems due to gases, because of the absence of moisture in the shell, and the little gas that is still present easily escapes through the thin shell. When the metal is poured some of the resin binder burns out on the surface of the shell, which makes shaking out easy.

One disadvantage is that the gating system must be part of the pattern because the entire mold is formed from the pattern, which can be expensive. Another is the resin for the sand is expensive, however not much is required because only a shell is being formed.