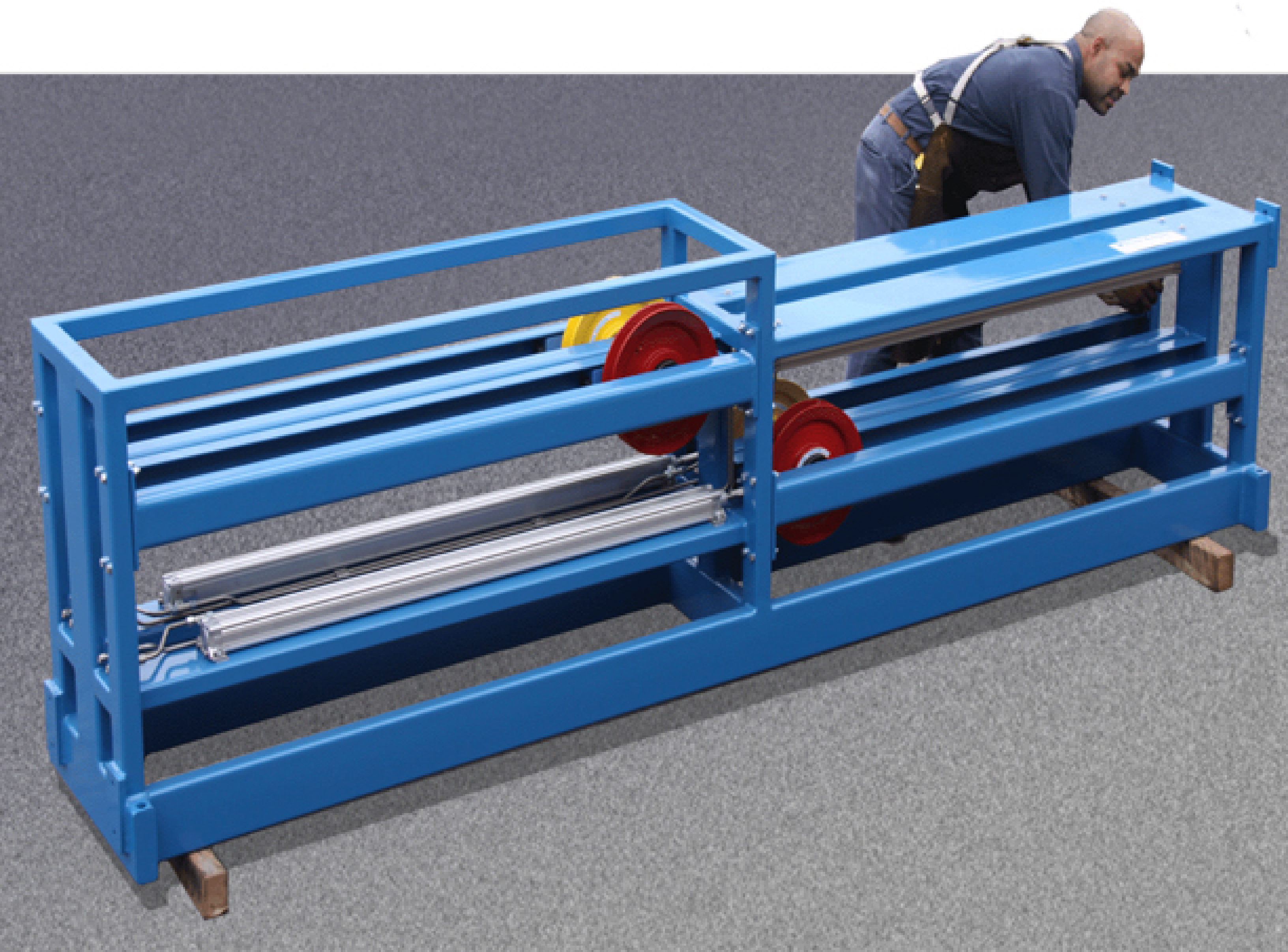
Metal Forming Engineering

Nilda Lyle



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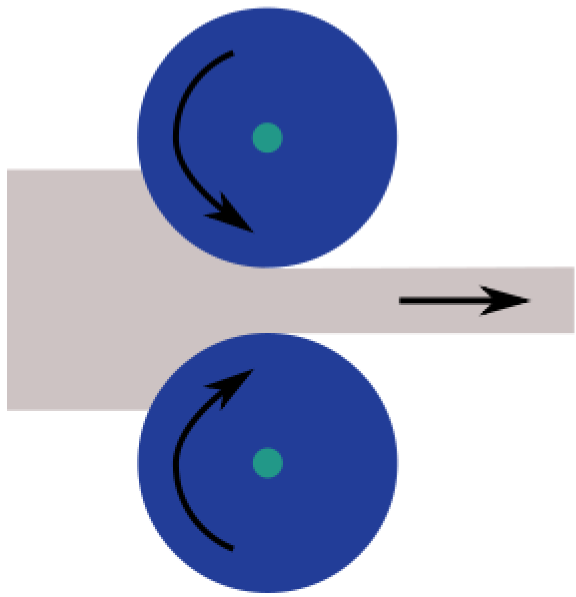
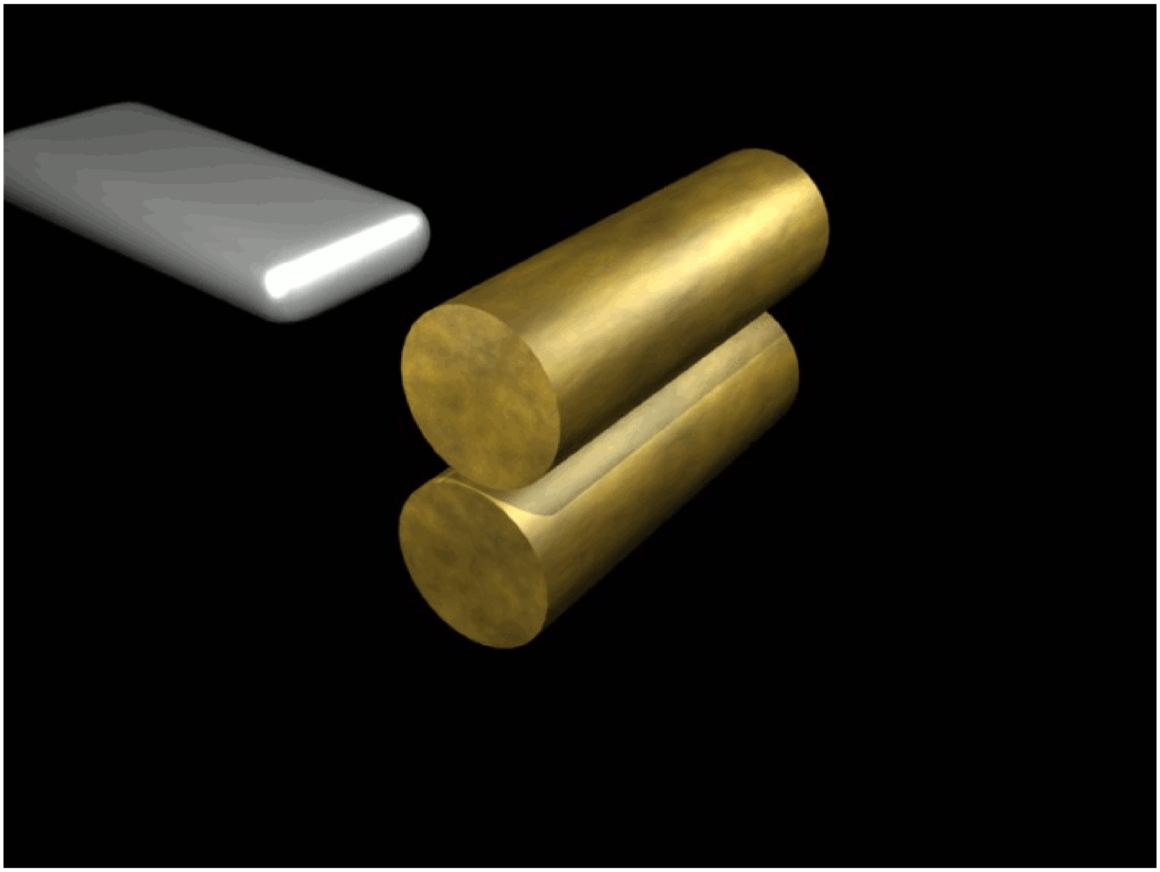
Rolling



A rolling schematic

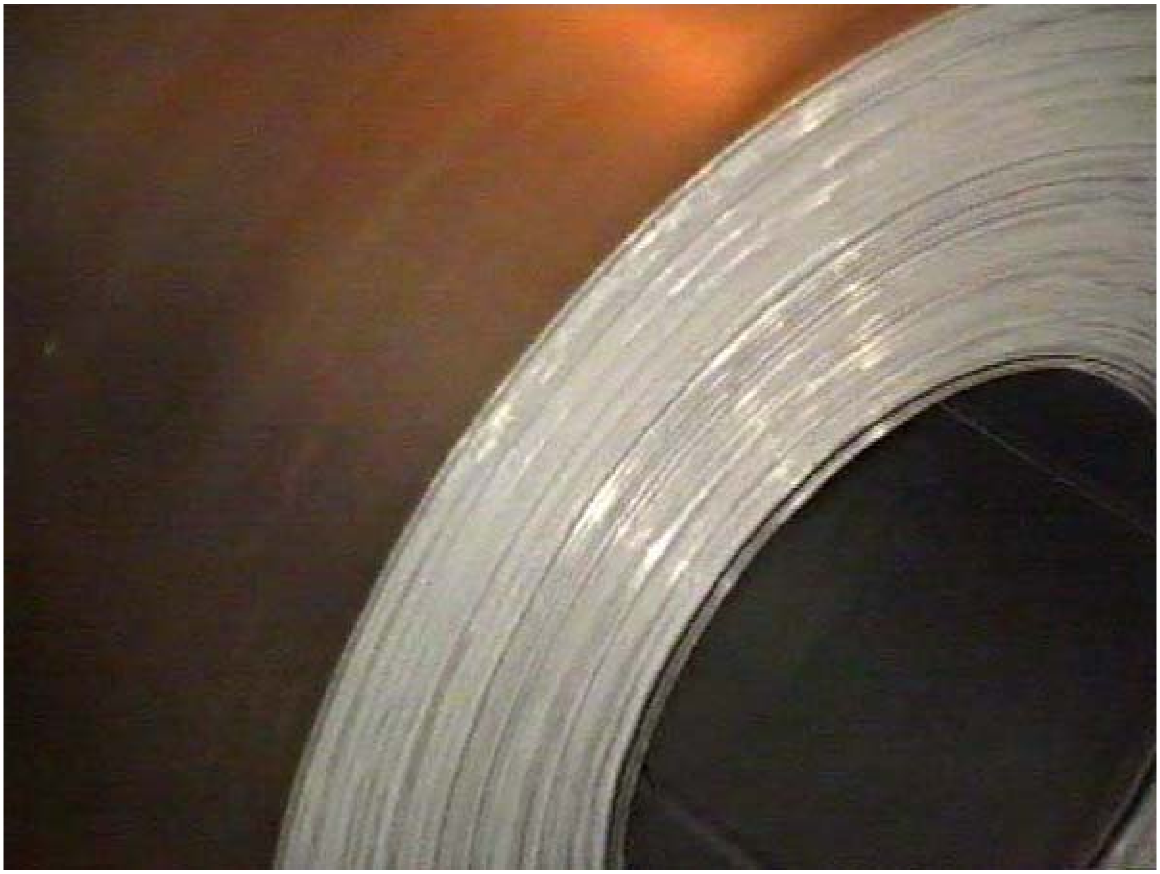


In metalworking, **rolling** is a metal forming process in which metal stock is passed through a pair of rolls. Rolling is classified according to the temperature of the metal rolled. If the temperature of the metal is above its recrystallization temperature, then the process is termed as **hot rolling**. If the temperature of the metal is below its recrystallization temperature, the process is termed as **cold rolling**. In terms of usage, hot rolling processes more tonnage than any other manufacturing process and cold rolling processes the most tonnage out of all cold working processes.

There are many types of rolling processes, including *flat rolling*, *foil rolling*, *ring rolling*, *roll bending*, *roll forming*, *profile rolling*, and *controlled rolling*.

Temperature

Hot rolling



A coil of hot-rolled steel

Hot rolling is a metalworking process that occurs above the recrystallization temperature of the material. After the grains deform during processing, they recrystallize, which maintains an equiaxed microstructure and prevents the metal from work hardening. The starting material is usually large pieces of metal, like semi-finished casting products, such as slabs, blooms, and billets. If these products came from a continuous casting operation the products are usually fed directly into the rolling mills at the proper temperature. In smaller operations the material starts at room temperature and must be heated. This is done in a gas- or oil-fired soaking pit for larger workpieces and for smaller workpieces induction heating is used. As the material is worked the temperature must be monitored to make sure it remains above the recrystallization temperature. To maintain a safety factor a *finishing temperature* is defined above the recrystallization temperature; this is usually 50 to 100 °C (122 to 212 °F) above the recrystallization temperature. If the temperature does drop below this temperature the material must be re-heated before more hot rolling.

Hot rolled metals generally have little directionality in their mechanical properties and deformation induced residual stresses. However, in certain instances non-metallic inclusions will impart some directionality and workpieces less than 20 mm (0.79 in) thick often have some directional properties. Also, non-uniformed cooling will induce a lot of residual stresses, which usually occurs in shapes that have a non-uniform cross-section, such as I-beams and H-beams. While the finished product is of good quality, the surface is covered in mill scale, which is an oxide that forms at high-temperatures. It is usually removed via pickling or the smooth clean surface process, which reveals a smooth surface. Dimensional tolerances are usually 2 to 5% of the overall dimension.

Hot rolling is used mainly to produce sheet metal or simple cross sections, such as rail tracks.

Cold rolling

A coil of cold-rolled steel

Cold rolling occurs with the metal below its recrystallization temperature (usually at room temperature), which increases the strength via strain hardening up to 20%. It also improves the surface finish and holds tighter tolerances. Commonly cold-rolled products include sheets, strips, bars, and rods; these products are usually smaller than the same products that are hot rolled. Because of the smaller size of the workpieces and their greater strength, as compared to hot rolled stock, four-high or cluster mills are used. Cold rolling cannot reduce the thickness of a workpiece as much as hot rolling in a single pass.

Cold-rolled sheets and strips come in various conditions: *full-hard*, *half-hard*, *quarter-hard*, and *skin-rolled*. Full-hard rolling reduces the thickness by 50%, while the others involve less of a reduction. Quarter-hard is defined by its ability to be bent back onto itself along the grain boundary without breaking. Half-hard can be bent 90°, while full-hard can only be bent 45°, with the bend radius approximately equal to the material thickness. Skin-rolling, also known as a *skin-pass*, involves the least amount of reduction: 0.5-1%. It is used to produce a smooth surface, a uniform thickness, and reduce the yield-point phenomenon (by preventing Luder bands from forming in later processing). It is also used to breakup the spangles in galvanized steel. Skin-rolled stock is usually used in subsequent cold-working processes where good ductility is required.

Other shapes can be cold-rolled if the cross-section is relatively uniform and the transverse dimension is relatively small; approximately less than 50 mm (2.0 in). This may be a cost-effective alternative to extruding or machining the profile if the volume is in the several tons or more. Cold rolling shapes requires a series of shaping operations, usually along the lines of: sizing, breakdown, roughing, semi-roughing, semi-finishing, and finishing.

Processes

Flat rolling

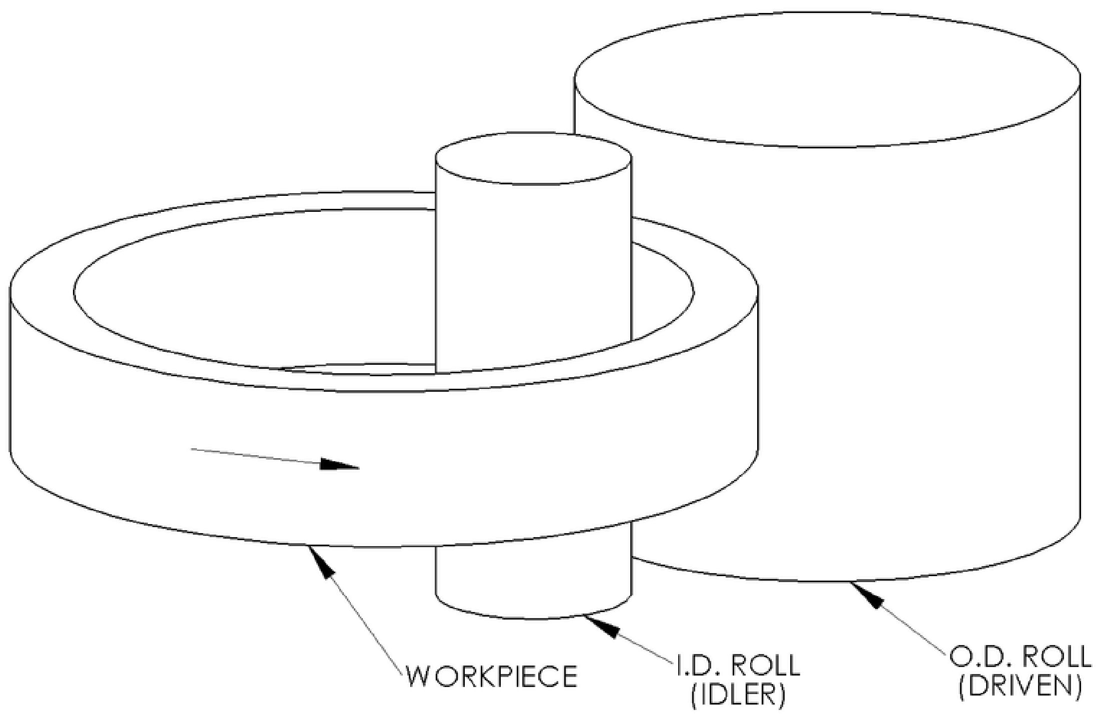
Flat rolling is the most basic form of rolling with the starting and ending material having a rectangular cross-section. The material is fed in between two *rollers*, called *working rolls*, that rotate in opposite directions. The gap between the two rolls is less than the thickness of the starting material, which causes it to deform. The decrease in material thickness causes the material to elongate. The friction at the interface between the material and the rolls causes the material to be pushed through. The amount of deformation possible in a single pass is limited by the friction between the rolls; if the change in thickness is too great the rolls just slip over the material and do not draw it in. The final product is either sheet or plate, with the former being less than 6 mm (0.24 in) thick and the latter greater than; however, heavy plates tend to be formed using a press, which is termed *forming*, rather than rolling.

Oftentimes the rolls are heated to assist in the workability of the metal. Lubrication is often used to keep the workpiece from sticking to the rolls. To fine tune the process the speed of the rolls and the temperature of the rollers are adjusted.

Foil rolling

Foil rolling is a specialized type of flat rolling, specifically used to produce foil, which is sheet metal with a thickness less than 200 µm (0.0079 in). The rolling is done in a *cluster mill* because the small thickness requires a small diameter rolls. To reduce the need for small rolls *pack rolling* is used, which rolls multiple sheets together to increase the effective starting thickness. As the foil sheets come through the rollers, they are trimmed and slitted with circular or razor-like knives. Trimming refers to the edges of the foil, while slitting involves cutting it into several sheets. Aluminum foil is the most commonly produced product via pack rolling. This is evident from the two different surface finishes; the shiny side is on the roll side and the dull side is against the other sheet of foil.

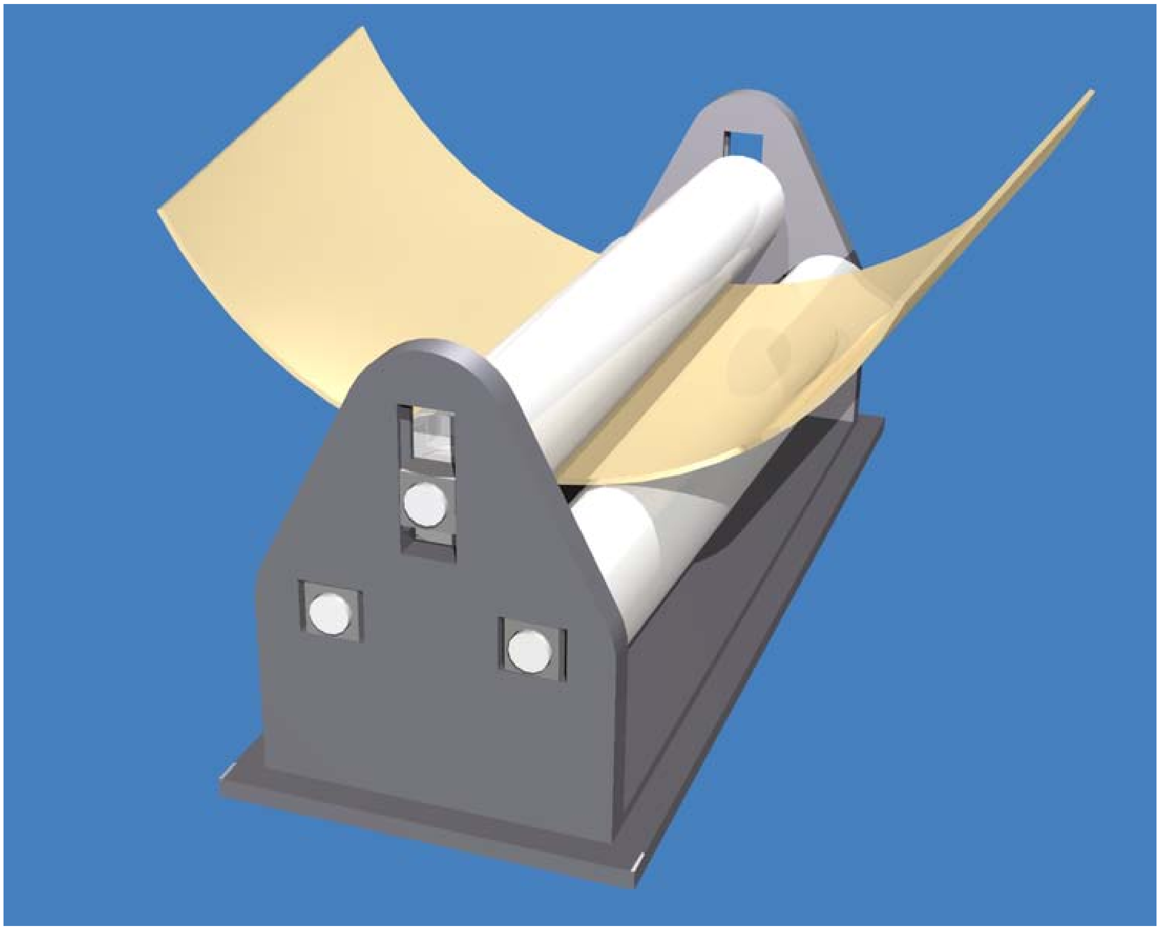
Ring rolling



A schematic of ring rolling

Ring rolling is a specialized type of hot rolling that increases the diameter of a ring. The starting material is a thick-walled ring. This workpiece is placed on an *idler roll*, while another roll, called the *driven roll*, presses the ring from the outside. As the rolling occurs the wall thickness decreases as the diameter increases. The rolls may be shaped to form various cross-sectional shapes. The resulting grain structure is circumferential, which gives better mechanical properties. Diameters can be as large as 8 m (26 ft) and face heights as tall as 2 m (79 in). Common applications include rockets, turbines, airplanes, pipes, and pressure vessels.

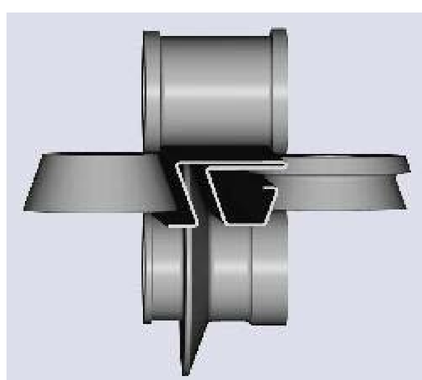
Roll bending



Roll bending

Roll bending produces a cylindrical shaped product from plate or steel metal.

Roll forming



Roll forming

Roll forming is a continuous bending operation in which a long strip of metal (typically coiled steel) is passed through consecutive sets of rolls, or stands, each performing only an incremental part of the bend, until the desired cross-section profile is obtained. Roll forming is ideal for producing parts with long lengths or in large quantities.

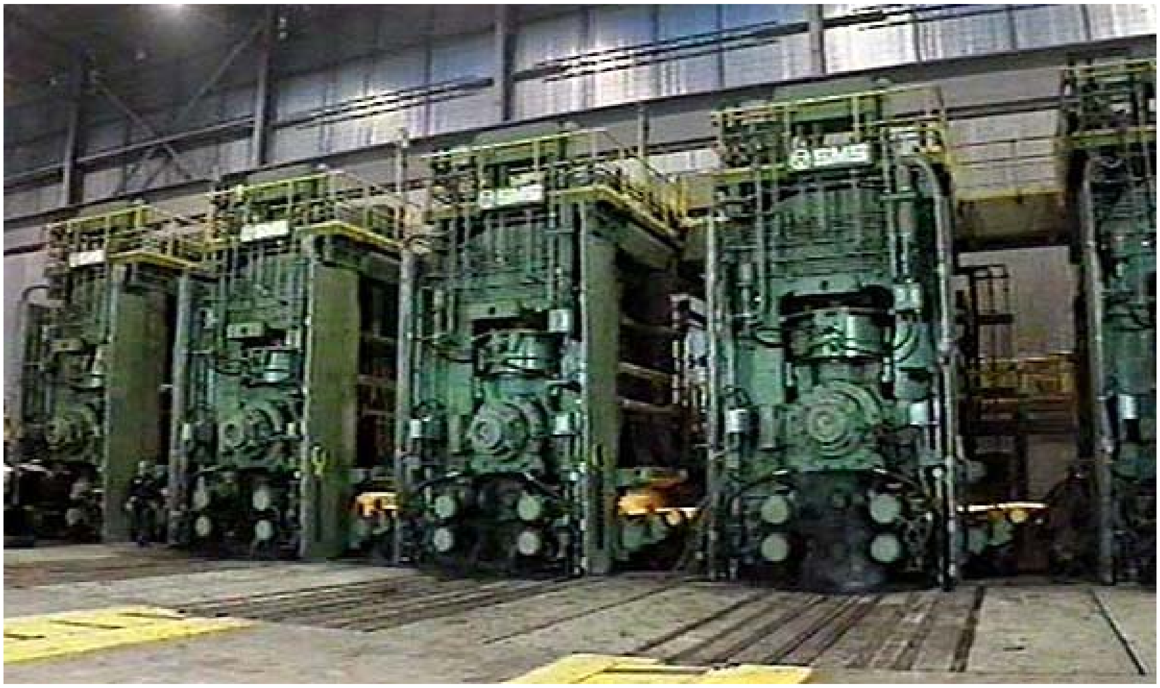
Structural shape rolling

Cross-sections of continuously rolled structural shapes, showing the change induced by each rolling mill.

Controlled rolling

Controlled rolling is a type of thermomechanical processing which integrates controlled deformation and heat treating. The heat which brings the workpiece above the recrystallization temperature is also used to perform the heat treatments so that any subsequent heat treating is unnecessary. Types of heat treatments include the production of a fine grain structure; controlling the nature, size, and distribution of various transformation products (such as ferrite, austenite, pearlite, bainite, and martensite in steel); inducing precipitation hardening; and, controlling the toughness. In order to achieve this the entire process must be closely monitored and controlled. Common variables in controlled rolling include the starting material composition and structure, deformation levels, temperatures at various stages, and cool-down conditions. The benefits of controlled rolling include better mechanical properties and energy savings.

Mills



Rolling mills

Rolling mill for cold rolling metal sheet like this piece of brass sheet

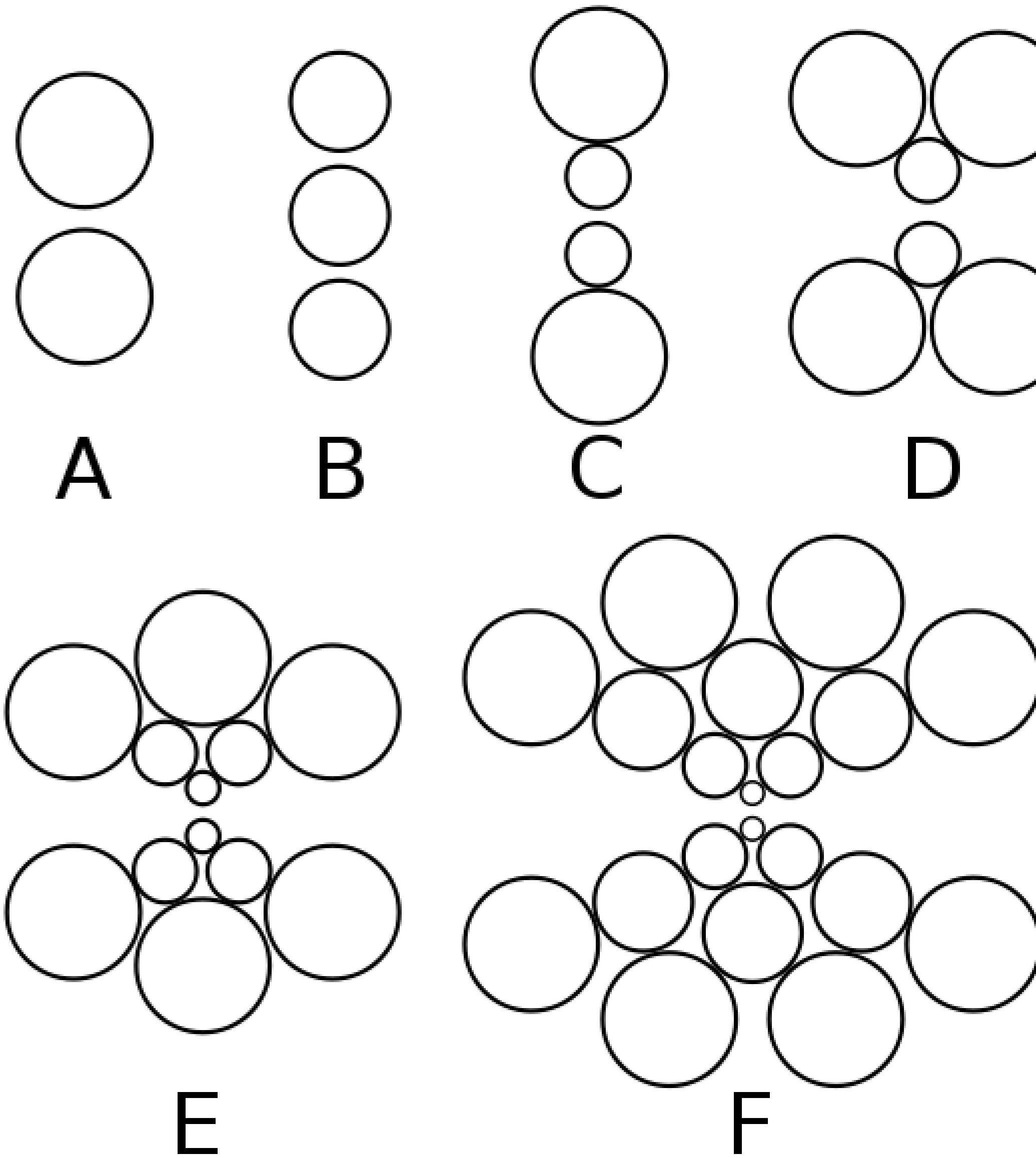
A *rolling mill*, also known as a *reduction mill* or *mill*, has a common construction independent of the specific type of rolling being performed:

- Work rolls
- Backup rolls - are intended to provide rigid support required by the working rolls to prevent bending under the rolling load
- Rolling balance system - to ensure that the upper work and back up rolls are maintain in proper position relative to lower rolls
- Roll changing devices - use of an overhead crane and a unit designed to attach to the neck of the roll to be removed from or inserted into the mill.

- Mill protection devices - to ensure that forces applied to the backup roll chocks are not of such a magnitude to fracture the roll necks or damage the mill housing
- Roll cooling and lubrication systems
- Pinions - gears to divide power between the two spindles, rotating them at the same speed but in different directions
- Gearing - to establish desired rolling speed
- Drive motors - rolling narrow foil product to thousands of horsepower
- Electrical controls - constant and variable voltages applied to the motors
- Coilers and uncoilers - to unroll and roll up coils of metal

Slabs are the feed material for hot strip mills or plate mills and blooms are rolled to billets in a billet mill or large sections in a structural mill. The output from a strip mill is coiled and, subsequently, used as the feed for a cold rolling mill or used directly by fabricators. Billets, for re-rolling, are subsequently rolled in either a merchant, bar or rod mill. Merchant or bar mills produce a variety of shaped products such as angles, channels, beams, rounds (long or coiled) and hexagons.

Configurations



Various rolling configurations. Key: A. 2-high B. 3-high C. 4-high D. 6-high E&F. Cluster

Mills are designed in different types of configurations, with the most basic being a *two-high non-reversing*, which means there are two rolls that only turn in one direction. The *two-high reversing* mill has rolls that can rotate in both directions, but the disadvantage is that the rolls must be stopped, reversed, and then brought back up to rolling speed between each pass. To resolve this, the *three-high* mill was invented, which uses three rolls that rotate in one direction; the metal is fed through two of the rolls and then returned through the other pair. The disadvantage to this system is the workpiece must be lifted and lowered using an elevator. All of these mills are usually used for primary rolling and the roll diameters range from 60 to 140 cm (24 to 55 in).

To minimize the roll diameter a *four-high* or *cluster* mill is used. A small roll diameter is advantageous because less roll is in contact with the material, which results in a lower force and energy requirement. The problem with a small roll is a reduction of stiffness, which is overcome using *backup rolls*. These backup rolls are larger and contact the back side of the smaller rolls. A four-high mill has four rolls, two small and two large. A cluster mill has more than 4 rolls, usually in three tiers. These types of mills are commonly used to hot roll wide plates, most cold rolling applications, and to roll foils.

Historically mills were classified by the product produced:

- Blooming, cogging and slabbing mills, being the preparatory mills to rolling finished rails, shapes or plates, respectively. If reversing, they are from 34 to 48 inches in diameter, and if three-high, from 28 to 42 inches in diameter.
- Billet mills, three-high, rolls from 24 to 32 inches in diameter, used for the further reduction of blooms down to 1.5x1.5-inch billets, being the preparatory mills for the bar and rod
- Beam mills, three-high, rolls from 28 to 36 inches in diameter, for the production of heavy beams and channels 12 inches and over.
- Rail mills with rolls from 26 to 40 inches in diameter.
- Shape mills with rolls from 20 to 26 inches in diameter, for smaller sizes of beams and channels and other structural shapes.
- Merchant bar mills with rolls from 16 to 20 inches in diameter.
- Small merchant bar mills with finishing rolls from 8 to 16 inches in diameter, generally arranged with a larger size roughing stand.
- Rod and wire mills with finishing rolls from 8 to 12 inches in diameter, always arranged with larger size roughing stands.
- Hoop and cotton tie mills, similar to small merchant bar mills.
- Armour plate mills with rolls from 44 to 50 inches in diameter and 140 to 180-inch body.
- Plate mills with rolls from 28 to 44 inches in diameter.
- Sheet mills with rolls from 20 to 32 inches in diameter.
- Universal mills for the production of square-edged or so-called universal plates and various wide flanged shapes by a system of vertical and horizontal rolls.

Tandem mill

A tandem mill is a special type of modern rolling mill where rolling is done in one pass. In a traditional rolling mill rolling is done in several passes, but in tandem mill there are several *stands* and reductions take place successively. The number of stands ranges from 2 to 18. Tandem mill can be either hot or cold rolling mill type.

Defects

In hot rolling, if the temperature of the workpiece is not uniform the flow of the material will occur more in the warmer parts and less in the cooler. If the temperature difference is great enough cracking and tearing can occur.

Shape

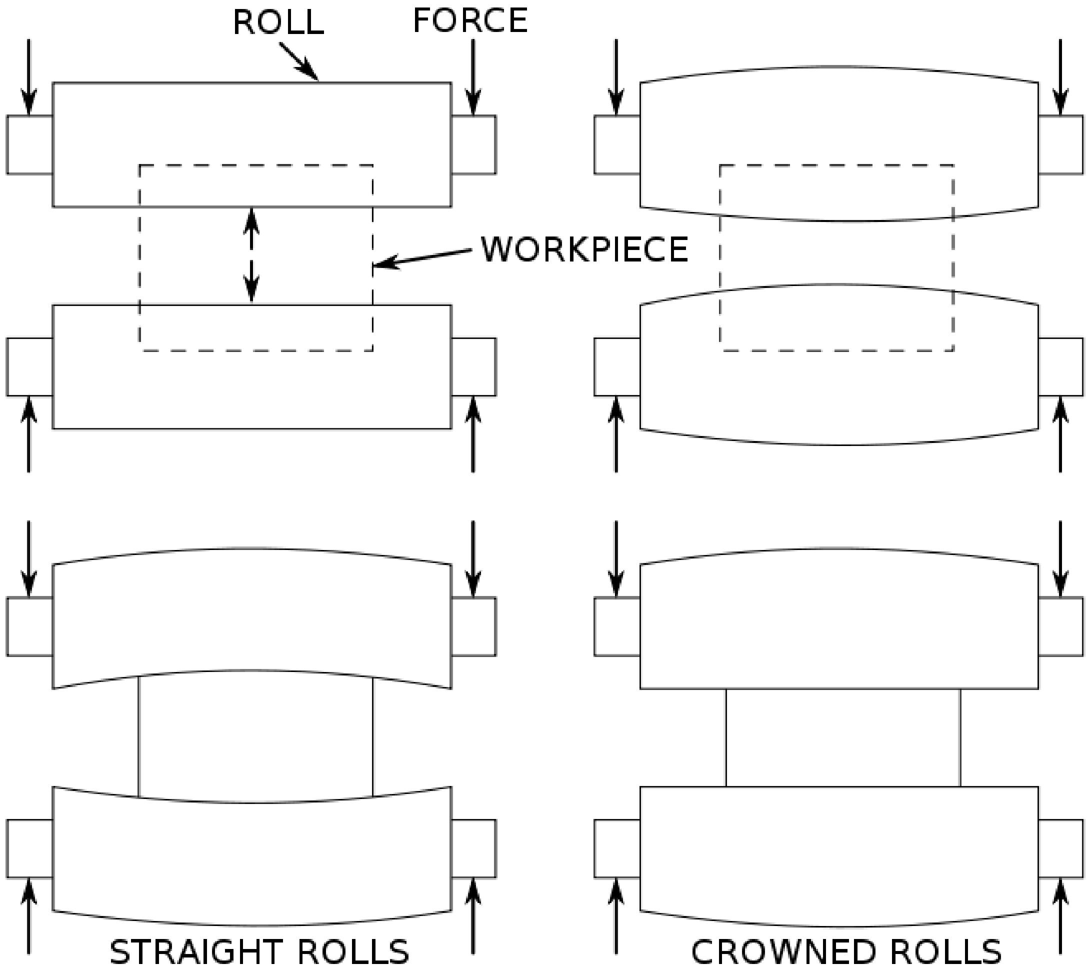
The term shape is used to describe the flatness and the profile of the workpiece. The profile consists of the how the thickness of the workpiece varies across the width of the workpiece and can be measured in units of length (typically micrometers or mils). The flatness of the workpiece is based on how the fiber elongation varies across the width of the workpiece and it typically measured in I-Units.

Profile

Profile is made up of the measurements of crown and wedge. Crown is the thickness in the center as compaired to the average thickness at the edges of the workpiece. Wedge is a measure of the thickness at one edge as opposed to the other edge. Both may be expressed as absolute measurments or as relative measurements. For instance, one could have 2 mil of crown (the center of the workpiece is 2 mil thicker than the edges), or one could have 2% crown (the center of the workpiece is 2% thicker than the edges).

It is typically desirable to have some crown in the workpiece as this will cause the workpiece to tend to pull to the center of the mill, and thus will run with higher stability.

Flatness



Roll deflection

Maintaining a uniform gap between the rolls is difficult because the rolls deflect under the load required to deform the workpiece as the work rolls act as a cantalever on the strip. The deflection causes the workpiece to be thinner on the edges and thicker in the middle. This can be overcome by using a crowned roller (parabolic crown), however the crowned roller will only compensate for one set of conditions, specifically the material, temperature, and amount of deformation.

Othere methods of compensating for roll deformation include CVC (continual varying crown), Pair cross rolling, and work roll bending. CVC was developed by SMS and involves grinding a third order polynomial curve into the work rolls and then shifting the work rolls laterally, equally, and opposite to each other. The effect is that the rolls will have a gap between them that is parabolic in shape, and will vary with lateral shift, thus allowing for control of the crown of the rolls dynamically. Pair cross rolling involves using either flat or parabolically crowned rolls, but shifting the ends at an angle so that the gap between the edges of the rolls will increase or decrease, thus allowing for dynamic crown control. Work roll bending involves using hydraulic cylinders at the ends of the rolls to counteract roll deflection.

Another way to overcome defection issues is by decreasing the load on the rolls, which can be done by applying an longitudinal force; this is essentially drawing; However, applying this longitudinal force has a tendency to hide the shape defect from the naked eye, so this could result in no action being taken to correct the shape defect. Other method of decreasing roll defection include increasing the elastic modulus of the roll material and adding back-up supports to the rolls.

The different classifications for flatness defects are: Symmetrical edge wave - the edges on both sides of the workpiece are "wavey" due to the material at the edges being longer than the material in the center. Asymmetrical edge wave - one edge is "wavey" due to the material at one side being longer than the other side. Center Buckle - The center of the strip is "wavey" due to the strip in the center being longer than the strip at the edges. Quarter Buckle - This is a rare defect where the fibers are elongated in the quarter regions (the portion of the strip between the center and the edge). This is normally attributed to using excessive roll bending force since the bending force may not compensate for the roll deflection across the entire length of the roll.

It is important to note that one could have a flatness defect even with the workpiece having the same thickness across the width. Also, one could have fairly high crown or wedge, but still produce material that is flat. In order to produce flat material, the material must be reduced by the same percentage across the width. This is important because mass flow of the material must be perserved, and the more a material is reduced, the more it is elongated. If a material is elongated in the same manner across the width, then the flatness coming into the mill will be preserved at the exit of the mill.

Surface defects

There are six types of surface defects:

Lap
: This type of defect occurs when a corner or fin is folded over and rolled but not welded into the metal. They appear as seams across the surface of the metal.

Mill-shearing
: These defects occur as a feather like lap.

Rolled-in scale
: This occurs when mill scale is rolled into metal.

Scabs
: These are long patches of loose metal that have been rolled into the surface of the metal.

Seams
: They are open, broken lines that run along the length of the metal and caused by the presence of scale.

Slivers

Prominent surface ruptures.

History

Iron and steel

The earliest rolling mills were slitting mills, which were introduced from what is now Belgium to England in 1590. These passed flat bars between rolls to form a plate of iron, which was then passed between grooved rolls (slitters) to produce rods of iron. The first experiments at rolling iron for tinplate took place about 1670. In 1697, Major John Hanbury erected a mill at Pontypool to roll 'Pontypool plates'—blackplate. Later this began to be rerolled and tinned to make tinplate. The earlier production of plate iron in Europe had been in forges, not rolling mills.

The slitting mill was adapted to producing hoops (for barrels) and iron with a half-round or other sections by means that were the subject of two patents of c. 1679.

Some of the earliest literature on rolling mills can be traced back to Christopher Polhem in 1761 in *Patriotista Testamente*, where he mentions rolling mills for both plate and bar iron. He also explains how rolling mills can save on time and labor because a rolling mill can produce 10 to 20 and still more bars at the same time which is wanted to tilt only one bar with a hammer.

A patent was granted to Thomas Blockley of England in 1759 for the polishing and rolling of metals. Another patent was granted in 1766 to Richard Ford of England for the first tandem mill. A tandem mill is one in which the metal is rolled in successive stands; Ford’s tandem mill was for hot rolling of wire rods.

Other metals

Rolling mills for lead seem to have existed by the late 17th century. Copper and brass were also rolled by the late 18th century.

Modern rolling

The modern rolling practice can be contributed to the efforts of Henry Cort of Fontley Iron Mills, near Fareham, England. In 1783 a patent was issued to Henry Cort for his use of grooved rolls for rolling iron bars. With this new design mills were able to produce 15 times the output per day than with a hammer. Although Cort was not the first to use grooved rolls; he was the first to combine the use of all the best features of various ironmaking and shaping processes known at the time. Thus the term “father of modern rolling” was giving to him by modern writers.

The first rail rolling mill was established by John Birkenshaw in 1820 where he produced fish bellied wrought iron rails in lengths of 15 to 18 feet. With the advancement of technology in rolling mills the size of rolling mills grew rapidly along with the size products being rolled. Example of this was at The Great Exhibition in 1851 a plate 20 feet long, 3 ½ feet wide, and 7/16 of inch thick, weighed 1,125 pounds was exhibited by the Consett Iron Company. Further evolution of the rolling mill came with the introduction of Three-high mills in 1853 used for rolling heavy sections.

Chapter-2

Swaging

Swaging is a forging process in which the dimensions of an item are altered using a die or dies, into which the item is forced. Swaging is usually a cold working process; however, it is sometimes done as a hot working process.

The term **swage** can apply to the process of swaging (verb), or to a die or tool used for swaging (noun).

Manufacturing process

As a general manufacturing process swaging may be broken up into two categories. The first category of swaging involves the workpiece being forced through a confining die to reduce its diameter, similar to the process of drawing wire. This may also be referred to as "tube swaging." The second category involves two or more dies used to hammer a round workpiece into a smaller diameter. This process is usually called "rotary swaging" or "radial forging."

Tubes may be tagged (reduced in diameter to enable the tube to be initially fed through the die to then be pulled from the other side) using a rotary swager, which allows them to be drawn on a draw bench. Swaging is normally the method of choice for precious metals since there is no loss of material in the process.

Rotary swaging

Rotary swaging process is usually a cold working process, used to reduce the diameter, produce a taper, or add point to a round workpiece. It can also impart internal shapes in hollow workpieces through the use of a mandrel (the shape must have a constant cross-section). Swaging a bearing into a housing means flaring its groove's lips onto the chamfer of the housing.

A swaging machine works by using two or four split dies which separate and close up to 2000 times a minute. This action is achieved by mounting the dies into the machine's spindle which is rotated by a motor. The spindle is mounted inside a cage containing rollers (looks like a roller bearing). The rollers are larger than the cage so as the spindle spins the dies are pushed out to ride on the cage by centrifugal force, as the dies cross over the rollers they push the dies together because of their larger size. On a four-die machine, the number of rollers cause all dies to close at a time; if the number of rollers do not cause all pairs of dies to close at the same time then the machine is called a rotary forging machine, even though it is still a swaging process.

A variation of the rotary swager is the *creeping spindle* swaging machine where both the spindle and cage revolve in opposite directions, this prevents the production of fins between the dies where the material being swaged grows up the gap between the dies.

There are two basic types of rotary swaging machine, the standard (also known as a tagging machine), and the *butt swaging* machine. A butt swaging machine works by having sets of wedges that close the dies onto the workpiece by inserting them between the annular rollers and the dies, normally by the use of a foot pedal. A butt swaging machine can allow a workpiece to be inserted without the dies closing on it, for example a three foot workpiece can be inserted 12 inches and then the dies closed, drawn through until 12 inches remain and the dies are then released, the finished workpiece would then, for example, be four feet long but still of its initial diameter for a foot at each end.

Other types

Pipes and cables

The most common use of swaging is to attach fittings to pipes or cables (also called wire ropes); the parts loosely fit together, and a mechanical or hydraulic tool compresses and deforms the fitting, creating a permanent joint. Pipe flaring machines are another example. Flared pieces of pipe are sometimes known as "swage nipples," "pipe swages," "swedge nipples," or "reducing nipples."

Saw blade teeth

In sawmills, a swage is used to flare large bandsaw or circle saw teeth, which increases the width of the cut, called the kerf. A clamp attaches a mandrel and die to the tooth and the eccentric die is rotated, swaging the tip. A much earlier version of the same operation used a hardened, shaped swage die and a hand held hammer. Saw teeth formed in this way are sometimes referred to as being "set." A finishing operation, shaping, cold works the points on the tooth sides to flats. It might be considered as a side swage. This slightly reduces the tooth width but increases the operating time between "fittings." Swaging is a major advance over filing as the operation is faster, more precise and greatly extends the working life of a saw.

Firearms and ammunition

In internal ballistics, swaging describes the process of the bullet entering the barrel and being squeezed to conform to the rifling. Most firearm bullets are made slightly larger than the inside diameter of the barrel, so that they are swaged to engage the rifling and form a tight seal upon firing. Compare to obturate.

In ammunition manufacture, swaged bullets are bullets manufactured by swaging room temperature metals into a die to form it into the shape of a bullet. The other common manufacturing method is casting, which uses molten metals poured into a mold. Since metals expand when heated and contract when cooled, cast bullets must be cast with a mold slightly larger than the desired finish size, so that as the molten metal cools, it will harden at just the right point to shrink to the desired size. In contrast, swaged bullets, since they are formed at the temperature at which they will be used, can be formed in molds of the exact desired size. This means that swaged bullets are generally more precise than cast bullets. The swaging process also leads to fewer imperfections, since voids commonly found in casting would be pressed out in the swaging process. The swaging process in reference to cold flow of metals into bullets is the process not of squeezing the metals into smaller forms but rather pressing smaller thinner items to form into shorter and slightly wider shapes.

Individuals who make their own bullets usually are not aware of available manual specialized equipment and dies required for swaging bullets, and thus choose to make cast bullets. To get high precision results, it is common to cast the bullets slightly oversized, then swage the resulting castings through a die to do the final forming. Since the amount of pressure required to size the bullet is far less than that required to form a bullet, a simple mechanical press can be used, often the same press used for handloading ammunition.

Swaging bullets using the cold flow method with manual hand tools, presses and dies is often credited to Ted Smith, author of the 45-page book *The Bullet Swage Manual*. Swaging is used to form unjacketed bullets, usually made of a mix of lead and some antimony to improve working properties (lead alone is usually too soft). The styles of bullets swaged usually have a *wadcutter* or *semiwadcutter* profile.

Many reloading equipment manufacturers started by marketing both reloading and bullet swaging dies and equipment. Historically many swage dies sold by well known reloading manufacturing companies were actually made by Ted Smith in his die shop then stamped with the name of the marketing company.

All of the larger manufacturers of reloading equipment have abandoned making or marketing bullet swaging equipment due to the downturn in the popularity of the manual methods and the subsequent loss of sales. Currently there are only a few die makers who manufacture and market bullet swaging equipment. Three die and equipment makers, CH/4D, RCE, and Corbin, manufacture the bulk of bullet swaging equipment in the United States.

Rubber components with mold bonded metal sleeves

This process provides a more controlled and cost-effective alternative to 'shooting' the rubber part into a metal sleeve, where an intensive and less dependable secondary operation is needed to finish the product. A metal can with a bonding component (such as phosphate) is painted to the inside diameter, and molten rubber is injected into the metal sleeve. This creates a product that when cooled may be swaged to the desired size. The second reason for this is that the product is more reliable, and during the swaging process the rubber is more relaxed when the outside can to which the rubber is bonded has its diameter reduced, changing the springrate (K) values and dampening the co-efficient (C) of the rubber. After swaging, any inconsistencies in the metal and rubber have been minimized.

Suture needles

In surgery, the thread used in sutures is often swaged to an eyeless needle in order to prevent damage as the needle and suture thread are drawn through the wound.

Musical instrument repair

In musical instrument repair the usual term on both sides of the Atlantic is swedging, not swaging, though it is generally acknowledged that the former derives from the latter. Keyed instruments such as the clarinet, bassoon, oboe and flute need swedging when years of key movement has worn or compressed the metal of the hinge tube they swivel on and made it slightly shorter, so that the key can travel along the rod it is mounted on instead of being held firmly between the posts attaching the rod to the body of the instrument. This gives rise to floppy keys and a poor air-seal and needs to be corrected by lengthening (swedging) the hinge tube. This is a job that needs to be done by hand, and swedging pliers with highly-polished oval holes in the jaws to fit common sizes of hinge tubes are often used to achieve this, though various proprietary designs of swedging tools are available to do the same job more efficiently.

Car styling swage line

As swaging is a technique in which cold metal is formed over a grooved tool or swage, the term was adopted in the field of automotive styling to describe when two panels were brought together, an edge of one panel was swaged so to overlap the other to create the impression of one continuous surface. This usually occurred in the vicinity of the beltline or waistline. As styling and production evolved and one-piece doors became possible, the swage line had become a popular element—whether separating the colors with two-color paint schemes or hidden by beltline mouldings—becoming a feature line. Nowadays, the term refers to any raised, continuous, bodyside crease or feature line.

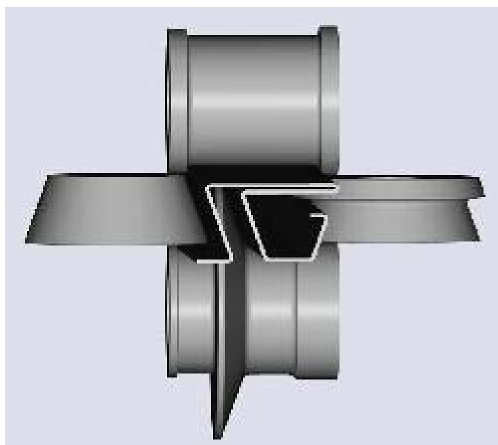
Lockbolts

Swaging is the generic term for setting a lockbolt and collar assembly. During the installation cycle of a lockbolt a collar, a loose fitting metal ring, is deformed around a pin with locking grooves. The tool engages onto the pintail, the joint is pulled together and the conical shaped cavity of the tooling is forced down the collar, which reduces its diameter and progressively swages the collar material into the grooves of the harder pin. As the force required for swaging increases during the process, the installation is finalised when the pintail breaks off.

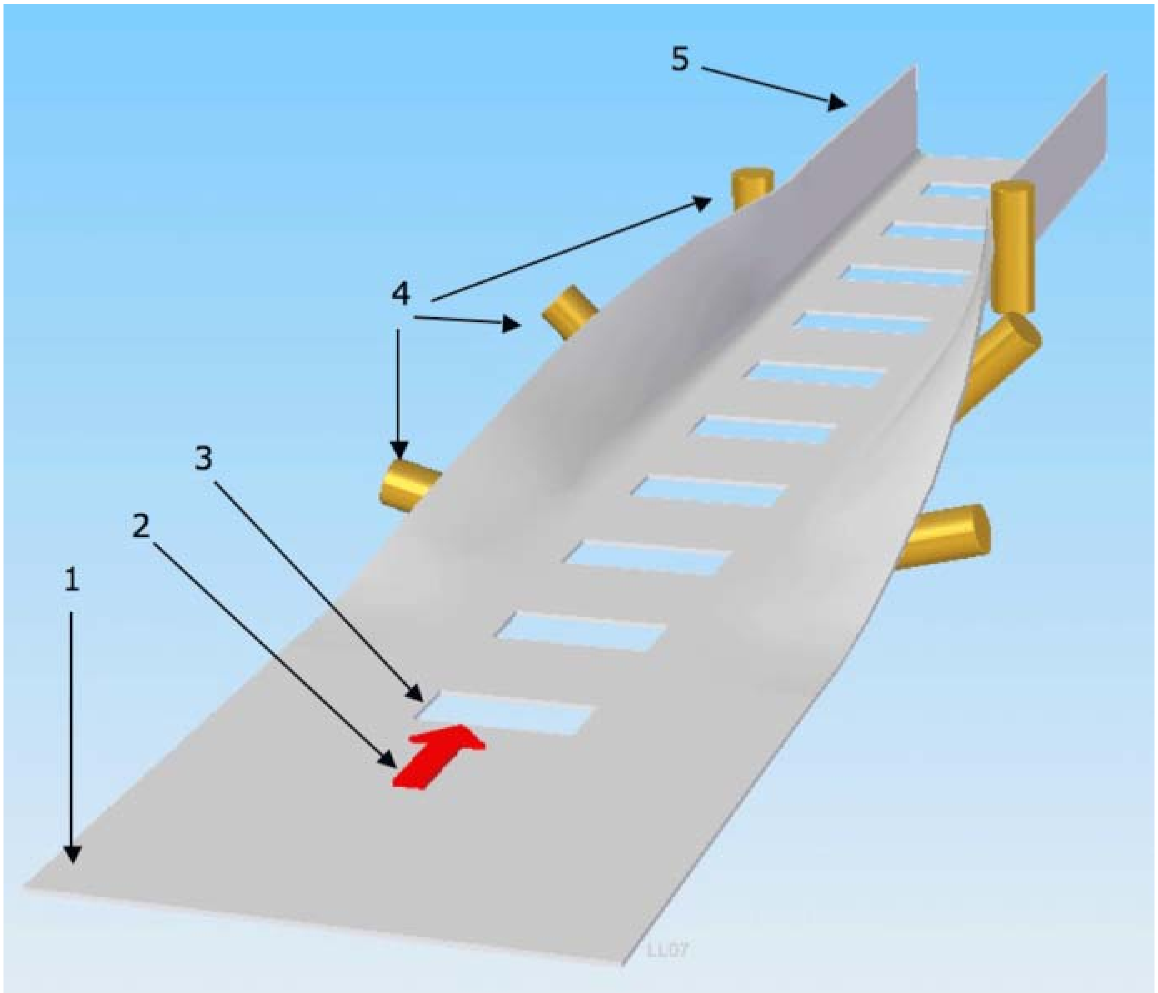
Chapter-3

Roll Forming and Metal Spinning

Roll forming



Roll forming stand



Roll Forming

Roll forming, also spelled **rollforming**, is a continuous bending operation in which a long strip of metal (typically coiled steel) is passed through consecutive sets of rolls, or **stands**, each performing only an incremental part of the bend, until the desired cross-section profile is obtained. Roll forming is ideal for producing parts with long lengths or in large quantities.

Overview

A variety of cross-section profiles can be produced, but each profile requires a carefully crafted set of roll tools. Design of the rolls starts with a **flower pattern**, which is the sequence of profile cross-sections, one for each stand of rolls. The roll contours are then derived from the profile contours. Because of the high cost of the roll sets, simulation is often used to validate the designed rolls and optimize the forming process to minimize the number of stands and material stresses in the final product.

Roll formed sections have an advantage over extrusions of a similar shapes. Roll formed parts are generally much lighter and stronger, having been work hardened in a cold state. Another advantage is that the part can be made having a finish or already painted. Labor is greatly reduced since volume is a major consideration for choosing the roll forming process.

Roll forming machines are now being produced so that for similar products such as stud and track profiles, a new set of profile rolls is not required. This is achieved by the mill being split along its center line and the web, flange and ear sizes are set using a control panel which moves the mill rafts centrally to increase or decrease the aforementioned features.

Roll forming lines can be set up with multiple configurations to punch and cut off parts in a continuous operation. For cutting a part to length, the lines can be set up to use a pre-cut die where a single blank runs through the roll mill, or a post-cut die where the profile is cutoff after the roll forming process. Features may be added in a hole, notch, embossment, or shear form by punching in a roll forming line. These part features can be done in a pre-punch application (before roll forming starts), in a mid-line punching application (in the middle of a roll forming line/process) or a post punching application (after roll forming is done). Some roll forming lines incorporate only one of the above punch or cutoff applications, others incorporate some or all of the applications in one line.

Process

The process of roll forming is one of the simpler manufacturing processes. It begins with a large spool of metal strips, usually between 1 in. and 20in. in width, and 0.004 in. and 0.125 in. thick. This is held by a device called a dispenser. The metal strip is then unrolled and fed into a machine starting with the stock feeder which is connected to the cutoff attachment. After the cutoff attachment, the metal strip is fed into the forming rolls. These mating die-set rolls are constructed to form the desired shape in stages sequentially by means of various shaped rolls. The layout of these rolls can be flower shaped as mentioned previously, progressive upper/lower rolls, side rolls, or as overhung spindle rolls (known as cluster roll configurations). These different roll configurations are used according to the job that needs to be done.

Geometric Possibilities

The geometric possibilities can be very broad and even include enclosed shapes so long as it is the same cross-section throughout. Typical sheeting thicknesses range from 0.004in. to 0.125in., but they can exceed that. Length is almost unaffected by the rolling process. The part widths typically aren't smaller than 1in. however they can exceed 20in.

- Tolerances can typically be held within ±0.015in. for the width of the cross-sectional form, and ±0.060in. for its depth.

Production Rates

The production rate depends greatly on the material thickness and the bend radius, it is also affected by the number of stations or steps required. For bend radii of 50 times the material thickness of a low carbon steel .07 in thick can range from 85 feet per minute through eight stations to 55 feet per minute through 12 stations or 50 feet per minute through 22 stations.
The time taken for one product to take shape can be represented by a simple function. The function is as follows: $Formingtime = L + n(d) / V$ where V is the velocity of strip through rolls (fpm), L is the length of the piece being rolled (ft), d is the distance between forming stands (ft), and n is the number of forming stands.

In General roll forming lines can run from 5 feet per minute to 500 + depending on the application. In some cases the limiting factor is the punching or cutoff applications.

Other Considerations

While dealing with manufacturing, there are always things to be considered such as lubrication, the effect of the process on material properties, cost, and of course safety. Lubrication provides an essential barrier between the roll dies and the workpiece surface. They help to reduce the tool wear, and allow things to move along faster. This table shows the different kinds of lubricants, their application, and the ideal metals to use them on.

Work Material	Roll Lubricants	Application
Nonferrous	Chlorinated oils or waxes, mineral oils	Spray, wiping roller
Ferrous	Water-soluble oils	Wiping, drip, spray
Stainless steels	Chlorinated oils or waxes	Wiping roller
Polished surfaces	Plastic film	Calendaring, covering, spraying
Precoated materials	Film/forced air	

The effects of the process on the material's properties for this process are very minimal. The physical and chemical properties virtually have no change. But the process may cause workhardening, microcracks, or thinning at bends when discussing the mechanical properties of the material.
The cost of roll forming is relatively low. Some things to be considered when calculating the cost of the process are setup time, equipment and tool costs, load/unload time, direct labor rate, overhead rate, and the amortization of equipment and tooling.
Safety is also a bit of an issue with this process. The main hazards that need to be taken

into consideration are dealing with moving workpieces (up to 800 fpm), high pressure rolls, or sharp, sheared metal edges.

Metal spinning

A brass vase spun by hand. Mounted to the lathe spindle is the mandrel for the body of the vase a shell sits on the "T" rest. The foreground shows the mandrel for the base. Behind the finished vase are the spinning tools used to shape the metal.

Metal spinning, also known as **spin forming** or **spinning**, is a metalworking process by which a disc or tube of metal is rotated at high speed and formed into an axially symmetric part. Spinning can be performed by hand or by a CNC lathe.

Metal spinning ranges from an artisan's specialty to the most advantageous way to form round metal parts for commercial applications. Artisans use the process to produce architectural detail, specialty lighting, decorative household goods and urns. Commercial applications include rocket nose cones, cookware, gas cylinders, brass instrument bells, and public waste receptacles. Virtually any ductile metal may be formed, from aluminum or stainless steel, to high-strength, high-temperature alloys. The diameter and depth of formed parts are limited only by the size of the equipment available.

Process

The spinning process is fairly simple. A formed block is mounted in the drive section of a lathe. A pre-sized metal disk is then clamped against the block by a pressure pad, which is attached to the tailstock. The block and workpiece are then rotated together at high speeds. A localized force is then applied to the workpiece to cause it to flow over the block. The force is usually applied via various levered tools. Simple workpieces are just removed from the block, but more complex shapes may require a multi-piece block. Extremely complex shapes can be spun over ice forms, which then melt away after spinning. Because the final diameter of the workpiece is always less than the starting diameter the workpiece must thicken, elongated radially, or buckle circumferentially.

A more involved process, known as *reducing* or *necking*, allows a spun workpiece to include reentrant geometries. If surface finish and form are not critical, then the workpiece is "spun on air"; no mandrel is used. If the finish or form are critical then an eccentrically mounted mandrel is used.

"Hot Spinning". This process involves spinning a piece of metal on a lathe and with high heat from a torch the metal is heated. Once heated, the metal is then shaped as the tool on the lathe presses against the heated surface forcing it to distort as it spins. Parts can then be shaped or necked down to a smaller diameter with little force exerted, providing a seamless shoulder.

Tools

The basic hand metal spinning tool is called a *spoon*, though many other tools (be they commercially produced, ad hoc, or improvised) can be used to effect varied results. Spinning tools can be made of hardened steel for using with aluminium or solid brass for spinning stainless steel or mild steel.

Some metal spinning tools are allowed to spin on bearings during the forming process. This reduces friction and heating of the tool, extending tool life and improving surface finish. Rotating tools may also be coated with thin film of ceramic to prolong tool life. Rotating tools are commonly used during CNC metal spinning operations.

Commercially, rollers mounted on the end of levers are generally used to form the material down to the mandrel in both hand spinning and CNC metal spinning. Rollers vary in diameter and thickness depending the intended use. The wider the roller the smoother the surface of the spinning; the thinner rollers can be used to form smaller radii.

Cutting of the metal is done by hand held cutters, often foot long hollow bars with tool steel shaped/sharpened files attached. In CNC applications, carbide or tool steel cut-off tools are used.

The mandrel does not incur excessive forces, as found in other metalworking processes, so it can be made from wood, plastic, or ice. For hard materials or high volume use, the mandrel is usually made of metal.

Advantages & disadvantages

Several operations can be performed in one set-up. Work pieces may have re-entrant profiles and the profile in relation to the center line virtually unrestricted.

Forming parameters and part geometry can be altered quickly, at less cost than other metal forming techniques. Tooling and production costs are also comparatively low. Spin forming, often done by hand, is easily automated and an effective production method for prototypes as well as high quantity production runs.

Other methods of forming round metal parts include hydroforming, stamping and forging or casting. Hydroforming and stamping generally have a higher fixed cost, but a lower variable cost than metal spinning. Forging or casting have a higher fixed cost due to the large equipment needed, but generally a lower variable cost. As machinery for commercial applications has improved, parts are being spun with thicker materials in excess of 1" thick steel. Conventional spinning also wastes a considerably smaller amount of material than other methods.

Objects can be built using one piece of material to produce parts without seams. Without seams, a part can withstand higher internal or external pressure exerted on it. For example: scuba tanks, CO_2 cartridges, and oxyacetylene tanks.

One disadvantage of metal spinning is that if a crack forms or the object is dented, it must be scrapped. Repairing the object is not cost-effective.

Chapter-4

Forging

Hot metal ingot being loaded into a hammer forge

Metal ingot after forging

Forging is a manufacturing process involving the shaping of metal using localized compressive forces. Forging is often classified according to the temperature at which it is performed: '"cold," "warm," or "hot" forging. Forged parts can range in weight from less than a kilogram to 580 metric tons. Forged parts usually require further processing to achieve a finished part.

History

Forging is one of the oldest known metalworking processes.

Traditionally, forging was performed by a smith using hammer and anvil, and though the use of water power in the production and working of iron dates to the 12th century, the hammer and anvil are not obsolete. The smithy or forge has evolved over centuries to become a facility with engineered processes, production equipment, tooling, raw materials and products to meet the demands of modern industry.

In modern times, industrial forging is done either with presses or with hammers powered by compressed air, electricity, hydraulics or steam. These hammers may have reciprocating weights in the thousands of pounds. Smaller power hammers, 500 lb (230 kg) or less reciprocating weight, and hydraulic presses are common in art smithies as well. Some steam hammers remain in use, but they became obsolete with the availability of the other, more convenient, power sources.

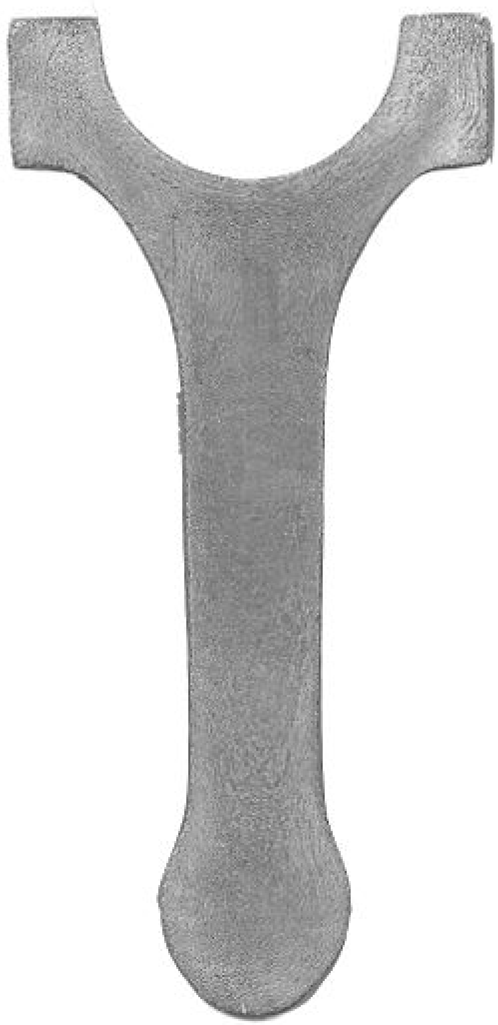
Advantages and disadvantages

Forging can produce a piece that is stronger than an equivalent cast or machined part. As the metal is shaped during the forging process, its internal grain deforms to follow the general shape of the part. As a result, the grain is continuous throughout the part, giving rise to a piece with improved strength characteristics.

Some metals may be forged cold, however iron and steel are almost always hot forged. Hot forging prevents the work hardening that would result from cold forging, which would increase the difficulty of performing secondary machining operations on the piece. Also, while work hardening may be desirable in some circumstances, other methods of hardening the piece, such as heat treating, are generally more economical and more controllable. Alloys that are amenable to precipitation hardening, such as most aluminium alloys and titanium, can be hot forged, followed by hardening.

Production forging involves significant capital expenditure for machinery, tooling, facilities and personnel. In the case of hot forging, a high temperature furnace (sometimes referred to as the forge) will be required to heat ingots or billets. Owing to the massiveness of large forging hammers and presses and the parts they can produce, as well as the dangers inherent in working with hot metal, a special building is frequently required to house the operation. In the case of drop forging operations, provisions must be made to absorb the shock and vibration generated by the hammer. Most forging operations will require the use of metal-forming dies, which must be precisely machined and carefully heat treated to correctly shape the workpiece, as well as to withstand the tremendous forces involved.

Processes



A cross-section of a forged connecting rod that has been etched to show the grain flow.

There are many different kinds of forging processes available, however they can be grouped into three main classes:

- Drawn out: length increases, cross-section decreases
- Upset: Length decreases, cross-section increases
- Squeezed in closed compression dies: produces multidirectional flow

Common forging processes include: roll forging, swaging, cogging, open-die forging, impression-die forging, press forging, automatic hot forging and upsetting.

Temperature

All of the following forging processes can be performed at various temperatures, however they are generally classified by whether the metal temperature is above or below the recrystallization temperature. If the temperature is above the material's recrystallization temperature it is deemed *hot forging*; if the temperature is below the material's recrystallization temperature but above 3/10ths of the recrystallization temperature (on an absolute scale) it is deemed *warm forging*; if below 3/10ths of the recrystallization temperature (usually room temperature) then it is deemed *cold forging*. The main advantage of hot forging is that as the metal is deformed work hardening effects are negated by the recrystallization process. Cold forging typically results in work hardening of the piece.

Drop forging

Drop forging is a forging process where a hammer is raised up and then "dropped" onto the workpiece to deform it according to the shape of the die. There are two types of drop forging: *open-die drop forging* and *closed-die drop forging*. As the names imply, the difference is in the shape of the die, with the former not fully enclosing the workpiece, while the latter does.

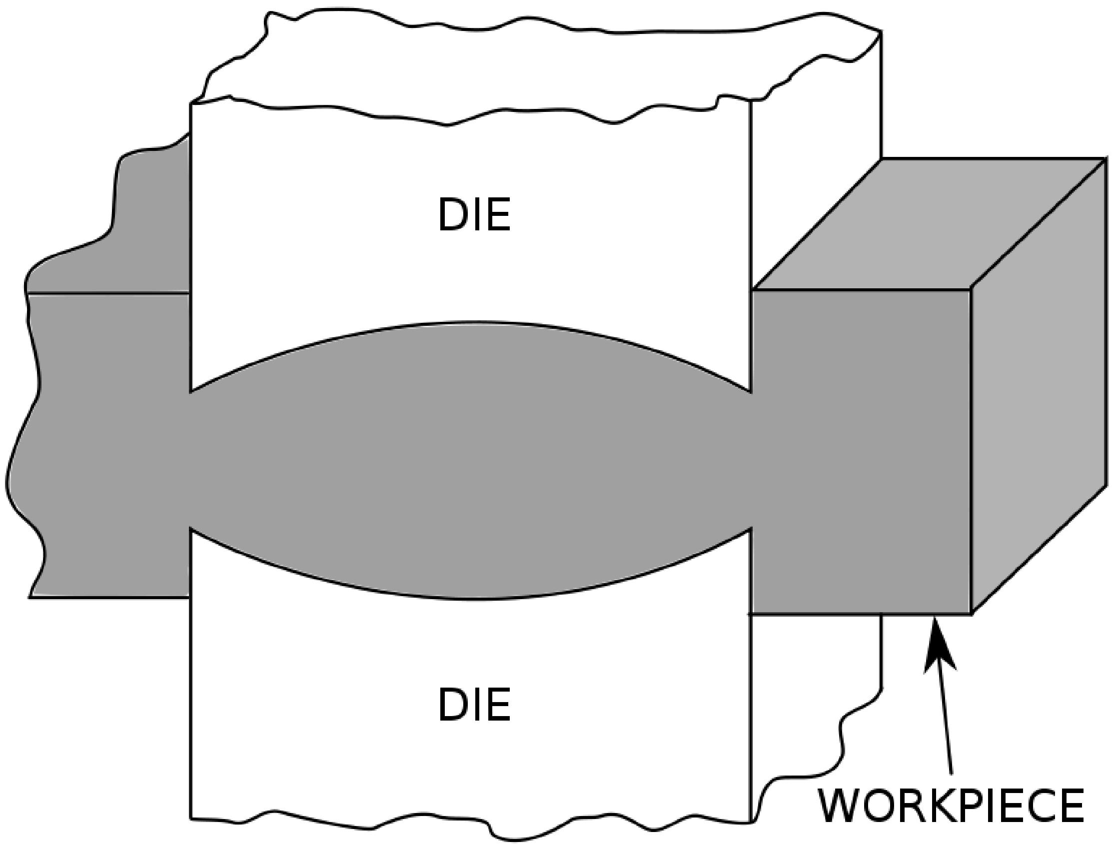
Open-die drop forging

Open-die forging is also known as *smith forging*. In open-die forging, a hammer strikes and deforms the workpiece, which is placed on a stationary anvil. Open-die forging gets its name from the fact that the dies (the surfaces that are in contact with the workpiece) do not enclose the workpiece, allowing it to flow except where contacted by the dies. Therefore the operator needs to orient and position the workpiece to get the desired shape. The dies are usually flat in shape, but some have a specially shaped surface for specialized operations. For example, a die may have a round, concave, or convex surface or be a tool to form holes or be a cut-off tool.

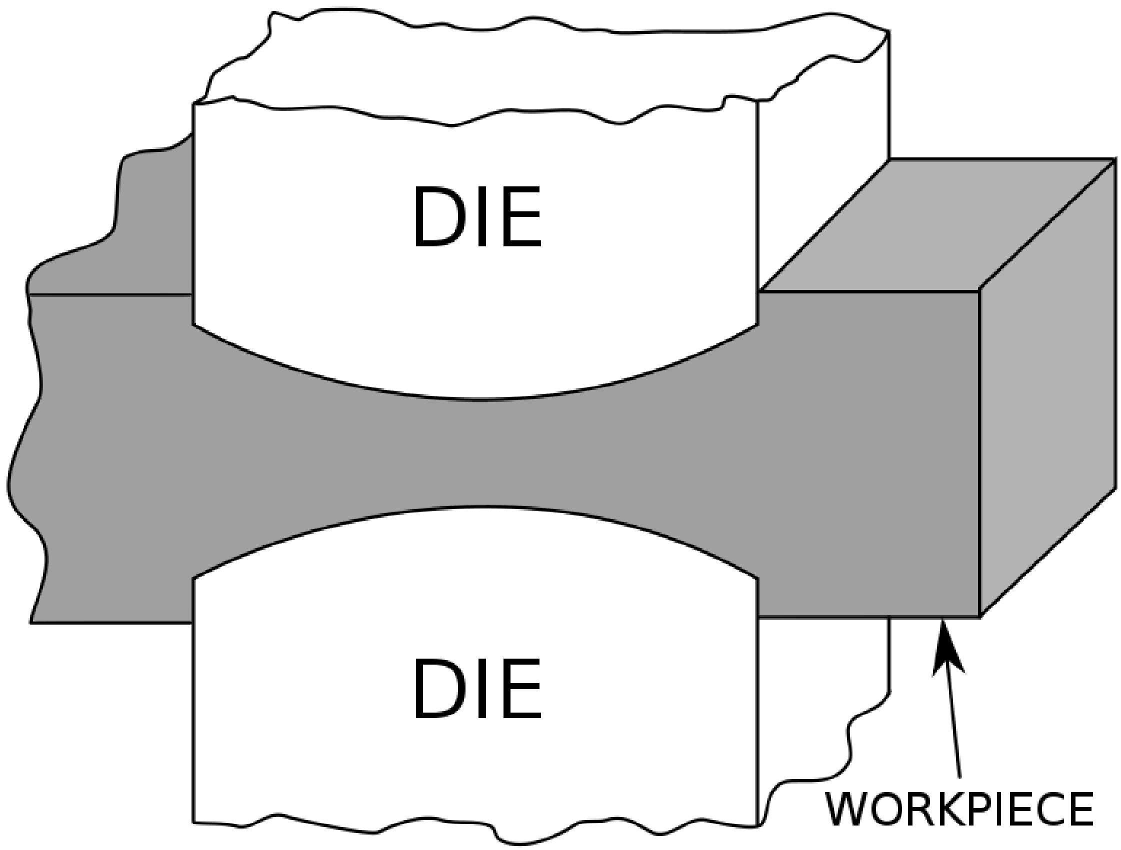
Open-die forging lends itself to short runs and is appropriate for art smithing and custom work. In some cases, open-die forging may be employed to rough-shape ingots to prepare them for subsequent operations. Open-die forging may also orient the grain to increase strength in the required direction.

Cogging is successive deformation of a bar along its length using an open-die drop forge. It is commonly used to work a piece of raw material to the proper thickness. Once the proper thickness is achieved the proper width is achieved via *edging*.

Edging is the process of concentrating material using a concave shaped open die. The process is called edging, because it is usually carried out on the ends of the workpiece. *Fullering* is a similar process that thins out sections of the forging using a convex shaped die. These processes prepare the workpieces for further forging processes.



Edging



Fullering

Impression-die drop forging

Impression-die forging is also called closed-die forging. In impression-die work metal is placed in a die resembling a mold, which is attached to the anvil. Usually the hammer die is shaped as well. The hammer is then dropped on the workpiece, causing the metal to flow and fill the die cavities. The hammer is generally in contact with the workpiece on the scale of milliseconds. Depending on the size and complexity of the part the hammer may be dropped multiple times in quick succession. Excess metal is squeezed out of the die cavities, forming what is referred to as *flash*. The flash cools more rapidly than the rest of the material; this cool metal is stronger than the metal in the die so it helps prevent more flash from forming. This also forces the metal to completely fill the die cavity. After forging the flash is removed.

In commercial impression-die forging the workpiece is usually moved through a series of cavities in a die to get from an ingot to the final form. The first impression is used to distribute the metal into the rough shape in accordance to the needs of later cavities; this impression is called an *edging*, *fullering*, or *bending* impression. The following cavities are called *blocking* cavities, in which the piece is working into a shape that more closely resembles the final product. These stages usually impart the workpiece with generous bends and large fillets. The final shape is forged in a *final* or *finisher* impression cavity. If there is only a short run of parts to be done it may be more economical for the die to lack a final impression cavity and instead machine the final features.

Impression-die forging has been further improved in recent years through increased automation which includes induction heating, mechanical feeding, positioning and manipulation, and the direct heat treatment of parts after forging.

One variation of impression-die forging is called *flashless forging*, or *true closed-die forging*. In this type of forging the die cavities are completely closed, which keeps the workpiece from forming flash. The major advantage to this process is that less metal is lost to flash. Flash can account for 20 to 45% of the starting material. The disadvantages of this process include additional cost due to a more complex die design and the need for better lubrication and workpiece placement.

There are other variations of part formation that integrate impression-die forging. One method incorporates casting a forging *preform* from liquid metal. The casting is removed after it has solidified, but while still hot. It is then finished in a single cavity die. The flash is trimmed, then the part is quench hardened. Another variation follows the same process as outlined above, except the preform is produced by the spraying deposition of metal droplet into shaped collectors (similar to the Osprey process).

Closed-die forging has a high initial cost due to the creation of dies and required design work to make working die cavities. However, it has low recurring costs for each part, thus forgings become more economical with more volume. This is one of the major reasons closed-die forgings are often used in the automotive and tool industry. Another reason forgings are common in these industrial sectors is because forgings generally have about a 20 percent higher strength-to-weight ratio compared to cast or machined parts of the same material.

Design of impression-die forgings and tooling

Forging dies are usually made of high-alloy or tool steel. Dies must be impact resistant, wear resistant, maintain strength at high temperatures, and have the ability to withstand cycles of rapid heating and cooling. In order to produce a better, more economical die the following rules should be followed:

- The dies should part along a single, flat plane if at all possible. If not the parting plane should follow the contour of the part.
- The parting surface should be a plane through the center of the forging and not near an upper or lower edge.
- Adequate draft should be provided; a good guideline is at least 3° for aluminum and 5° to 7° for steel
- Generous fillets and radii should be used
- Ribs should be low and wide
- The various sections should be balanced to avoid extreme difference in metal flow
- Full advantage should be taken of fiber flow lines

- Dimensional tolerances should not be closer than necessary

The dimensional tolerances of a steel part produced using the impression-die forging method are outlined in the table below. It should be noted that the dimensions across the paring plane are affected by the closure of the dies, and are therefore dependent die wear and the thickness of the final flash. Dimensions that are completely contained within a single die segment or half can be maintained at a significantly greater level of accuracy.

Dimensional tolerances for impression-die forgings

Mass [kg (lb)]	Minus tolerance [mm (in)]	Plus tolerance [mm (in)]
0.45 (1)	0.15 (0.006)	0.48 (0.018)
0.91 (2)	0.20 (0.008)	0.61 (0.024)
2.27 (5)	0.25 (0.010)	0.76 (0.030)
4.54 (10)	0.28 (0.011)	0.84 (0.033)
9.07 (20)	0.33 (0.013)	0.99 (0.039)
22.68 (50)	0.48 (0.019)	1.45 (0.057)
45.36 (100)	0.74 (0.029)	2.21 (0.087)

A lubricant is always used when forging to reduce friction and wear. It is also used to as a thermal barrier to restrict heat transfer from the workpiece to the die. Finally, the lubricant acts as a parting compound to prevent the part from sticking in one of the dies.

Press forging

Press forging works by slowly applying a continuous pressure or force, which differs from the near-instantaneous impact of drop-hammer forging. The amount of time the dies are in contact with the workpiece is measured in seconds (as compared to the milliseconds of drop-hammer forges). The press forging operation can be done either cold or hot.

The main advantage of press forging, as compared to drop-hammer forging, is its ability to deform the complete workpiece. Drop-hammer forging usually only deforms the surfaces of the workpiece in contact with the hammer and anvil; the interior of the workpiece will stay relatively undeformed. Another advantage to the process includes the knowledge of the new part's strain rate. We specifically know what kind of strain can be put on the part, because the compression rate of the press forging operation is controlled. There are a few disadvantages to this process, most stemming from the workpiece being in contact with the dies for such an extended period of time. The operation is a time consuming process due to the amount of steps and how long each of them take. The workpiece will cool faster because the dies are in contact with workpiece; the dies facilitate drastically more heat transfer than the surrounding atmosphere. As the workpiece cools it becomes stronger and less ductile, which may induce cracking if deformation continues. Therefore heated dies are usually used to reduce heat loss, promote surface flow, and enable the production of finer details and closer tolerances.

The workpiece may also need to be reheated. When done in high productivity, press forging is more economical than hammer forging. The operation also creates closer tolerances. In hammer forging a lot of the work is absorbed by the machinery, when in press forging, the greater percentage of work is used in the work piece. Another advantage is that the operation can be used to create any size part because there is no limit to the size of the press forging machine. New press forging techniques have been able to create a higher degree of mechanical and orientation integrity. By the constraint of oxidation to the outer most layers of the part material, reduced levels of microcracking take place in the finished part.

Press forging can be used to perform all types of forging, including open-die and impression-die forging. Impression-die press forging usually requires less draft than drop forging and has better dimensional accuracy. Also, press forgings can often be done in one closing of the dies, allowing for easy automation.

Upset forging

Upset forging increases the diameter of the workpiece by compressing its length. Based on number of pieces produced this is the most widely used forging process. A few examples of common parts produced using the upset forging process are engine valves, couplings, bolts, screws, and other fasteners.

Upset forging is usually done in special high speed machines called *crank presses*, but upsetting can also be done in a vertical crank press or a hydraulic press. The machines are usually set up to work in the horizontal plane, to facilitate the quick exchange of workpieces from one station to the next. The initial workpiece is usually wire or rod, but some machines can accept bars up to 25 cm (9.8 in) in diameter and a capacity of over 1000 tons. The standard upsetting machine employs split dies that contain multiple cavities. The dies open enough to allow the workpiece to move from one cavity to the next; the dies then close and the heading tool, or ram, then moves longitudinally against the bar, upsetting it into the cavity. If all of the cavities are utilized on every cycle then a finished part will be produced with every cycle, which is why this process is ideal for mass production.

The following three rules must be followed when designing parts to be upset forged:

- The length of unsupported metal that can be upset in one blow without injurious buckling should be limited to three times the diameter of the bar.
- Lengths of stock greater than three times the diameter may be upset successfully provided that the diameter of the upset is not more than 1.5 times the diameter of the stock.
- In an upset requiring stock length greater than three times the diameter of the stock, and where the diameter of the cavity is not more than 1.5 times the diameter of the stock, the length of unsupported metal beyond the face of the die must not exceed the diameter of the bar.

Automatic hot forging

The automatic hot forging process involves feeding mill-length steel bars (typically 7 m (23 ft) long) into one end of the machine at room temperature and hot forged products emerge from the other end. This all occurs very quickly; small parts can be made at a rate of 180 parts per minute (ppm) and larger can be made at a rate of 90 ppm. The parts can be solid or hollow, round or symmetrical, up to 6 kg (13 lb), and up to 18 cm (7.1 in) in diameter. The main advantages to this process are its high output rate and ability to accept low cost materials. Little labor is required to operate the machinery. There is no flash produced so material savings are between 20 and 30% over conventional forging. The final product is a consistent 1,050 °C (1,920 °F) so air cooling will result in a part that is still easily machinable (the advantage being the lack of annealing required after forging). Tolerances are usually ±0.3 mm (0.012 in), surfaces are clean, and draft angles are 0.5 to 1°. Tool life is nearly double that of conventional forging because contact times are on the order of 6/100 of a second. The downside to the process is it only feasible on smaller symmetric parts and cost; the initial investment can be over $10 million, so large quantities are required to justify this process.

The process starts by heating up the bar to 1,200 to 1,300 °C (2,192 to 2,372 °F) in less than 60 seconds using high power induction coils. It is then descaled with rollers, sheared into blanks, and transferred several successive forming stages, during which it is upset, preformed, final forged, and pierced (if necessary). This process can also be couple with high speed cold forming operations. Generally, the cold forming operation will do the finishing stage so that the advantages of cold-working can be obtained, while maintaining the high speed of automatic hot forging.

Examples of parts made by this process are: wheel hub unit bearings, transmission gears, tapered roller bearing races, stainless steel coupling flanges, and neck rings for LP gas cylinders. Manual transmission gears are an example of automatic hot forging used in conjunction with cold working.

Roll forging

Roll forging is a process where round or flat bar stock is reduced in thickness and increased in length. Roll forging is performed using two cylindrical or semi-cylindrical rolls, each containing one or more shaped grooves. A heated bar is inserted into the rolls and when it hits a stop the rolls rotate and the bar is progressively shaped as it is rolled out of the machine. The work piece is then transferred to the next set of grooves or turned around and reinserted into the same grooves. This continues until the desired shape and size is achieved. The advantage of this process is there is no flash and it imparts a favorable grain structure into the workpiece.

Examples of products produced using this method include axles, tapered levers and leaf springs.

Net-shape and near-net-shape forging

This process is also known as *precision forging*. This process was developed to minimize cost and waste associated with post forging operations. Therefore, the final product from a precision forging needs little to no final machining. Cost savings are gained from the use of less material, and thus less scrap, the overall decrease in energy used, and the reduction or elimination of machining. Precision forging also requires less of a draft, 1° to 0°. The downside of this process is its cost, therefore it is only implemented if significant cost reduction can be achieved.

Cost implications

To achieve a low cost net shape forging for demanding applications that are subject to a high degree of scrutiny, i.e. non-destructive testing by way of a dye-penetrant inspection technique, it is crucial that basic forging process disciplines are implemented. If the basic disciplines are not met, there is a high probability that subsequent material removal operations will be necessary to remove material defects found at non-destructive testing inspection. Hence low cost parts will not be achievable.

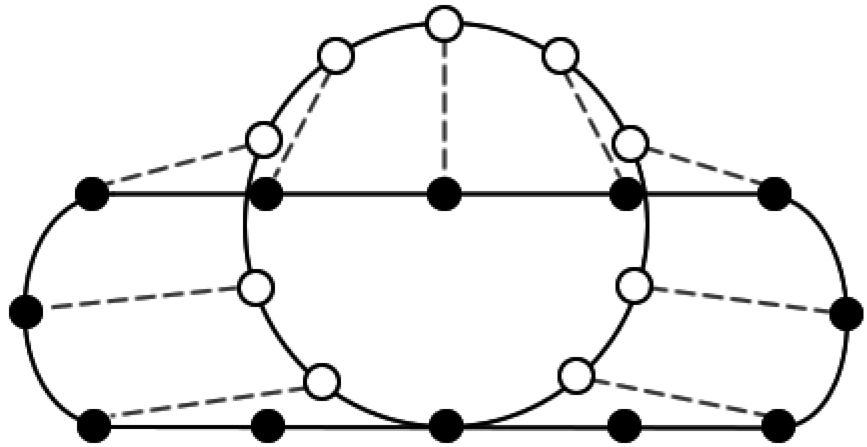
Example disciplines are: die-lubricant management (Use of uncontaminated and homogeneous mixtures, amount and placement of lubricant). Tight control of die temperatures and surface finish / friction.

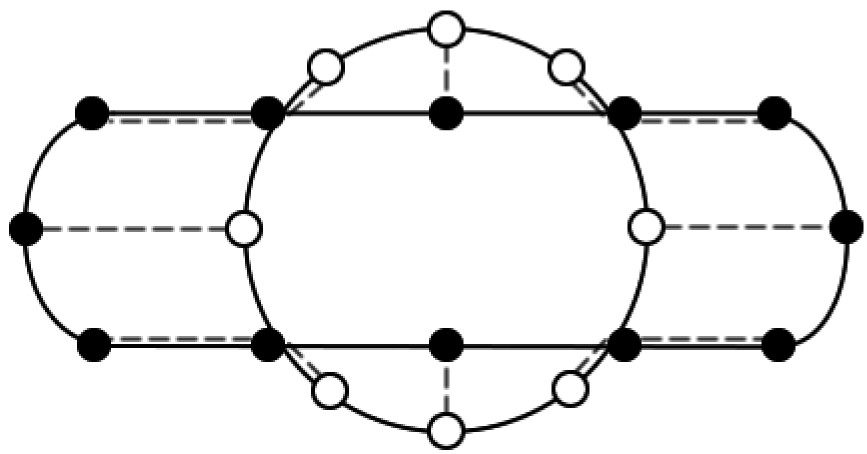
Induction forging

Unlike the above processes, induction forging is based on the type of heating style used. Many of the above processes can be used in conjunction with this heating method.

Equipment

Hydraulic drop-hammer





(a) Material flow of a conventionally forged disc; (b) Material flow of an impactor forged disc.

The most common type of forging equipment is the hammer and anvil. Principles behind the hammer and anvil are still used today in *drop-hammer* equipment. The principle behind the machine is very simple—raise the hammer and then drop it or propel it into the workpiece, which rests on the anvil. The main variations between drop-hammers are in the way the hammer is powered; the most common being air and steam hammers. Drop-hammers usually operate in a vertical position. The main reason for this is excess energy (energy that isn't used to deform the workpiece) that isn't released as heat or sound needs to be transmitted to the foundation. Moreover, a large machine base is needed to absorb the impacts.

To overcome some of the shortcomings of the drop-hammer, the *counterblow machine* or *impactor* is used. In a counterblow machine both the hammer and anvil move and the workpiece is held between them. Here excess energy becomes recoil. This allows the machine to work horizontally and consist of a smaller base. Other advantages include less noise, heat and vibration. It also produces a distinctly different flow pattern. Both of these machines can be used for open die or closed die forging.

A *forging press*, often just called a press, is used for press forging. There are two main types: mechanical and hydraulic presses. Mechanical presses function by using cams, cranks and/or toggles to produce a preset (a predetermined force at a certain location in the stroke) and reproducible stroke. Due to the nature of this type of system, different forces are available at different stroke positions. Mechanical presses are faster than their hydraulic counterparts (up to 50 strokes per minute). Their capacities range from 3 to 160 MN (300 to 18,000 short tons-force). Hydraulic presses use fluid pressure and a piston to generate force. The advantages of a hydraulic press over a mechanical press are its flexibility and greater capacity. The disadvantages include a slower, larger, and costlier machine to operate.

The roll forging, upsetting, and automatic hot forging processes all use specialized machinery.

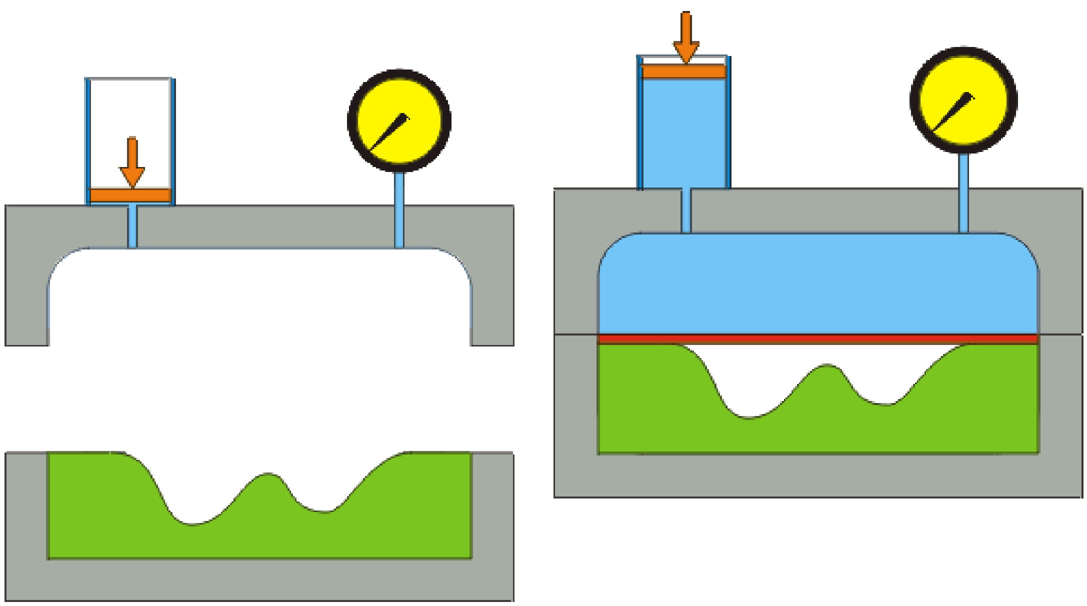
List of large forging presses

Force (tonnes)	Ingot size (tonnes)	Company	Country
16,000	600	Erzhong	China
15,000	580	China First Heavy Industries	China
14,000	600	Japan Steel Works	Japan
13,000		Doosan	South Korea

Chapter-5

Hydroforming and Punching

Hydroforming



Hydroforming (or **hydramolding**) is a cost-effective way of shaping malleable metals such as aluminum or brass into lightweight, structurally stiff and strong pieces. One of the largest applications of hydroforming is the automotive industry, which makes use of the complex shapes possible by hydroforming to produce stronger, lighter, and more rigid unibody structures for vehicles. This technique is particularly popular with the high-end sports car industry and is also frequently employed in the shaping of aluminium tubes for bicycle frames.

Hydroforming is a specialized type of die forming that uses a high pressure hydraulic fluid to press room temperature working material into a die. To hydroform aluminum into a vehicle's frame rail, a hollow tube of aluminum is placed inside a negative mold that has the shape of the desired end result. High pressure hydraulic pistons then inject a fluid at very high pressure inside the aluminum which causes it to expand until it matches the mold. The hydroformed aluminum is then removed from the mold.

Hydroforming allows complex shapes with concavities to be formed, which would be difficult or impossible with standard solid die stamping. Hydroformed parts can often be made with a higher stiffness to weight ratio and at a lower per unit cost than traditional stamped or stamped and welded parts.

This process is based on the 1950s patent for hydramolding by Fred Leuthesser, Jr. and John Fox of the Schaible Company of Cincinnati, OH. It was originally used in producing kitchen spouts. This was done because in addition to the strengthening of the metal, hydramolding also produced less "grainy" parts, allowing for easier metal finishing.

Process schematic

Sheet hydroforming

In sheet hydroforming there is Bladder forming (where there is a bladder that contains the liquid, no liquid contacts the sheet) and hydroforming where the fluid contacts the sheet (no bladder). A work piece is placed on a draw ring (blank holder) over a male punch then a hydraulic chamber surrounds the work piece and a relatively low initial pressure seats the work piece against the punch. The punch then is raised into the hydraulic chamber and pressure is increased to as high as 15000 psi which forms the part around the punch. Then the pressure is released and punch retracted and hydraulic chamber lifted and the process is complete.

Tube hydroforming

In tube hydroforming (THF) there are two major practices: high pressure and low pressure. With the high pressure process the tube is fully enclosed in a die prior to pressurization of the tube. In low pressure the tube is slightly pressurized to a fixed volume during the closing of the die (this used to be called the Variform process). In tube hydroforming pressure is applied to the inside of a tube that is held by dies with the desired cross sections and forms. When the dies are closed, the tube ends are sealed by axial punches and the tube is filled with hydraulic fluid. The internal pressure can go up to a few thousands of bars and it causes the tube to calibrate against the dies. The fluid is injected into the tube through one of the two axial punches. Axial punches are movable and their action is required to provide axial compression and to feed material towards the center of the bulging tube. Transverse counterpunches may also be incorporated in the forming die in order to form protrusions with small diameter/length ratio. Transverse counterpunches may also be used to punch holes in the work piece at the end of the forming process. Many industrial applications of the process can be found, especially in the automotive sector.

Explosive hydroforming

For large parts, explosive hydroforming can generate the forming pressure by simply exploding a charge above the part (complete with evacuated mold) which is immersed in a pool of water. The tooling can be much cheaper than what would be required for any press-type process. The hydroforming-into-a-mold process also works using only a shock wave in air as the pressuring medium. Particularly when the explosives are close to the workpiece, inertia effects make the result more complicated than forming by hydrostatic pressure alone.

Setup and equipment

Tools and punches can be interchanged for different part requirements.

Typical tools

One advantage of hydroforming is the savings on tools. For sheet metal only a draw ring and punch (metalworking) or male die is required. The bladder of the hydroform itself acts as the female die eliminating the need to fabricate a matching female die. This allows for changes in material thickness to be made with usually no necessary changes to the tool. However, dies must be highly polished and in tube hydroforming a two-piece die is required to allow opening and closing.

Geometry produced

Another advantage of hydroforming is that complex shapes can be made in one step. In sheet hydroforming (SHF) with the bladder acting as the female die almost limitless geometries can be produced. However, the process is limited by the very high closing force required in order to seal the dies, especially for large panels and thick hard materials. Small concave corner radii are difficult to be completely calibrated, i.e. filled, because too large a pressure would be required. Limits of the SHF process are due to risks of excessive thinning, fracture, wrinkling and are strictly related to the material formability and to a proper selection of process parameters (e.g. hydraulic pressure vs. time curve). Tube hydroforming (THF) can produce many geometric options as well, reducing the need for tube welding operations. Similar limitations and risks can be listed as in SHF; however, the maximum closing force is seldom a limiting factor in THF.

Tolerances and surface finish

Hydroforming is capable of producing parts within tight tolerances including aircraft tolerances where a common tolerance for sheet metal parts is within 0.76mm (thirty thousandths of an inch). Sheet metal hydroforming also allows for a smoother finish as draw marks produced by the traditional method of pressing a male and female die together are eliminated.

Effect on work material

When a blank is hydroformed the metal flows around the die rather than stretching, which produces less material thinning, and also reduces the rate of work hardening which helps eliminate the need for an annealing process on some parts that might otherwise require further forming operations.

Examples

Notable examples include:

- Satellite antennas up to 6 metres in diameter, such as those used in the Allen Telescope Array.
- The brass tube of Yamaha saxophones.
- The process has become popular for the manufacture of aluminium bicycle frames. The earliest commercially manufactured one being that of the Giant Manufacturing Revive bicycle first marketed in 2003.
- Many motor vehicles have major components manufactured using this technology, for example:
    - The technique is widely used in the manufacture of engine cradles. The first mass produced one was for the Ford Contour and Mystique in 1994. Others from a long list include the Pontiac Aztek, the Honda Accord and the perimeter frame around the Harley Davidson V-Rod motorcycle's engine.
    - As well as engine cradles, the main automotive applications for hydroforming are suspension, radiator supports and instrument-panel support beams. The first mass produced automotive component was in 1990 with the instrument panel support beam for the Chrysler minivan.
    - Various vehicle bodies and body components, the earliest mass produced one being the 1997 Chevrolet Corvette. A selection from many examples are the current versions of the three major United States pickup trucks -- the Ford F-150, Chevrolet Silverado, and Ram -- which all have hydroformed frame rails, 2006 Pontiac Solstice and the steel frame inside the John Deere HPX Gator Utility Vehicle.

Punching

Titanium nitride (TiN) coated industrial punches using Cathodic arc deposition technique

Punching is a metal forming process that uses a punch press to force a tool, called a **punch**, through the workpiece to create a hole via shearing. The punch often passes through the work into a die. A scrap slug from the hole is deposited into the die in the process. Depending on the material being punched this slug may be recycled and reused or discarded. Punching is often the cheapest method for creating holes in sheet metal in medium to high production. When a specially shaped punch is used to create multiple usable parts from a sheet of material the process is known as blanking. In forging applications the work is often punched while hot, and this is called hot punching.

Process

A punch is often made of hardened steel or carbides. A die is located on the opposite side of the workpiece and supports the material around the perimeter of the hole and helps to localize the shearing forces for a cleaner edge. There is a small amount of clearance between the punch and the die to prevent the punch from sticking in the die, and so less force is needed to make the hole. The amount of clearance needed depends on the thickness and hardness of the workpiece material. For ductile materials the clearance must be less than the thickness of the material being punched. The punch press forces the punch through a workpiece, producing a hole that has a diameter equivalent to the punch, or slightly smaller after the punch is removed. All ductile materials stretch to some extent during punching which often causes the punch to stick in the workpiece. In this case, the the punch must be physically pulled back out of the hole while the work is supported from the punch side, and this process is known as stripping. The hole walls will show burnished area, rollover, and die break and must often be further processed. The slug from the hole falls through the die into some sort of container to either dispose of the slug or recycle it.

Punching Characteristics

- Punching is the most cost effective process of making holes in strip or sheet metal for average to high fabrication
- It is able to create multiple shaped holes
- Punches and dies are usually fabricated from conventional tool steel or carbides
- Creates a burnished region roll-over, and die break on sidewall of the resulting hole

Geometry

The workpiece is often in the form of a sheet or roll. Materials for the workpiece can vary, commonly being metals and plastics. The punch and die themselves can have a variety of shapes to create an array of different shaped holes in the workpiece. Multiple punches may be used together to create a part in one step.

Equipment

Most punch presses are mechanically operated, but simple punches are often hand-powered. Major components of this mechanical press are the frame, motor, ram, die posts, bolster, and bed. The punch is mounted into the ram, and the die is mounted to the bolster plate. The scrap material drops through as the workpiece is advanced for the next hole. A large computer controlled punch press is called a computer numerical controlled turret. It houses punches and their corresponding dies in a revolving indexed turret. These machines use hydraulic, pneumatic, or electrical power to press the shape with enough force to shear the metal.

Forces

The punch force required to punch a piece of sheet metal can be estimated from the following equation:

$$F = 0.7tL(UTS)$$

Where t is the sheet metal thickness, L is the total length sheared (perimeter of the shape), and UTS is the ultimate tensile strength of the material.

Die and punch shapes affect the force during the punching process. The punch force increases during the process as the entire thickness of the material is sheared at once. A beveled punch helps in the shearing of thicker materials by reducing the force at the beginning of the stroke. However, beveling a punch will disort the shape because of lateral forces that develop. Compound dies allow multiple shaping to occur. Using compound dies will generally slow down the process and are typically more expensive than other dies. Progressive dies may be used in high production operations. Different punching operations and dies may be used at different stages of the operation on the same machine.

Related processes

Other processes such as stamping, blanking, perforating, parting, drawing, notching, lancing and bending operations are all related to punching.

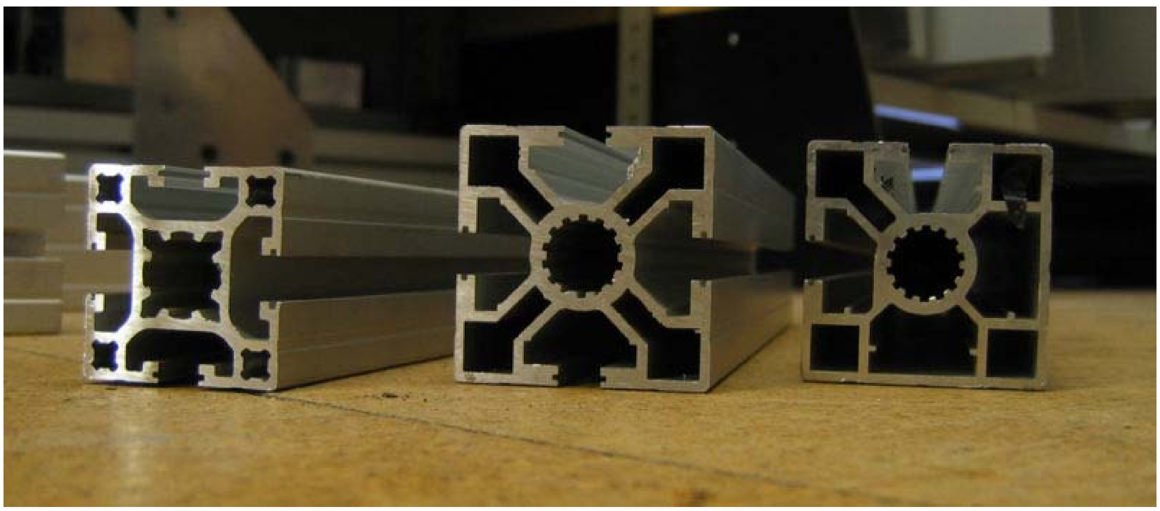
Plastics

Punching in plastics fabrication usually refers to the removal of scrap plastic from the desired article. For example, in extrusion blow molding it is common to use punching dies to remove tails, molding flash (scrap plastic) and handle slugs from bottles or other molded containers.

In shuttle machinery, the containers are usually trimmed in the machines, and finished containers leave the blow molding machine. Other blow molding equipment, such as rotary wheel machinery, requires the use of downstream trimming. Types of downstream trimming equipment include detabbers for tail removal, rotary or reciprocating punch trimmers, and spin trimmers.

Chapter-6

Extrusion



Extruded aluminium with several hollow cavities; slots allow bars to be joined with special connectors.

Extrusion is a process used to create objects of a fixed cross-sectional profile. A material is pushed or drawn through a die of the desired cross-section. The two main advantages of this process over other manufacturing processes are its ability to create very complex cross-sections and work materials that are brittle, because the material only encounters compressive and shear stresses. It also forms finished parts with an excellent surface finish.

Extrusion may be continuous (theoretically producing indefinitely long material) or semi-continuous (producing many pieces). The extrusion process can be done with the material hot or cold.

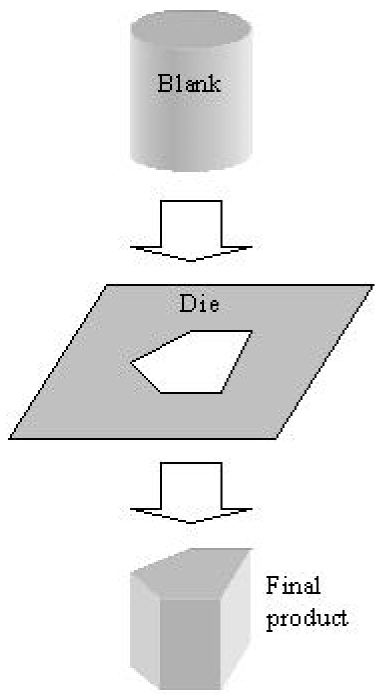
Commonly extruded materials include metals, polymers, ceramics, concrete and foodstuffs.

Hollow cavities within extruded material cannot be produced using a simple flat extrusion die, because there would be no way to support the center barrier of the die. Instead, the die assumes the shape of a block with depth, beginning first with a shape profile that supports the center section. The die shape then internally changes along its length into the final shape, with the suspended center pieces supported from the back of the die.

History

In 1797, Joseph Bramah patented the first extrusion process for making lead pipe. It involved preheating the metal and then forcing it through a die via a hand driven plunger. The process wasn't developed until 1820 when Thomas Burr constructed the first hydraulic powered press. At this time the process was called squirting. In 1894, Alexander Dick expanded the extrusion process to copper and brass alloys.

Process



Extrusion of a round blank through a die.

The process begins by heating the stock material (for hot or warm extrusion). It is then loaded into the container in the press. A dummy block is placed behind it where the ram then presses on the material to push it out of the die. Afterward the extrusion is stretched in order to straighten it. If better properties are required then it may be heat treated or cold worked.

The extrusion ratio is defined as the starting cross-sectional area divided by the cross-sectional area of the final extrusion. One of the main advantages of the extrusion process is that this ratio can be very large while still producing quality parts.

Hot extrusion

Hot extrusion is a hot working process, which means it is done above the material's recrystallization temperature to keep the material from work hardening and to make it easier to push the material through the die. Most hot extrusions are done on horizontal hydraulic presses that range from 230 to 11,000 metric tons (250 to 12,000 short tons). Pressures range from 30 to 700 MPa (4,400 to 100,000 psi), therefore lubrication is required, which can be oil or graphite for lower temperature extrusions, or glass powder for higher temperature extrusions. The biggest disadvantage of this process is its cost for machinery and its upkeep.

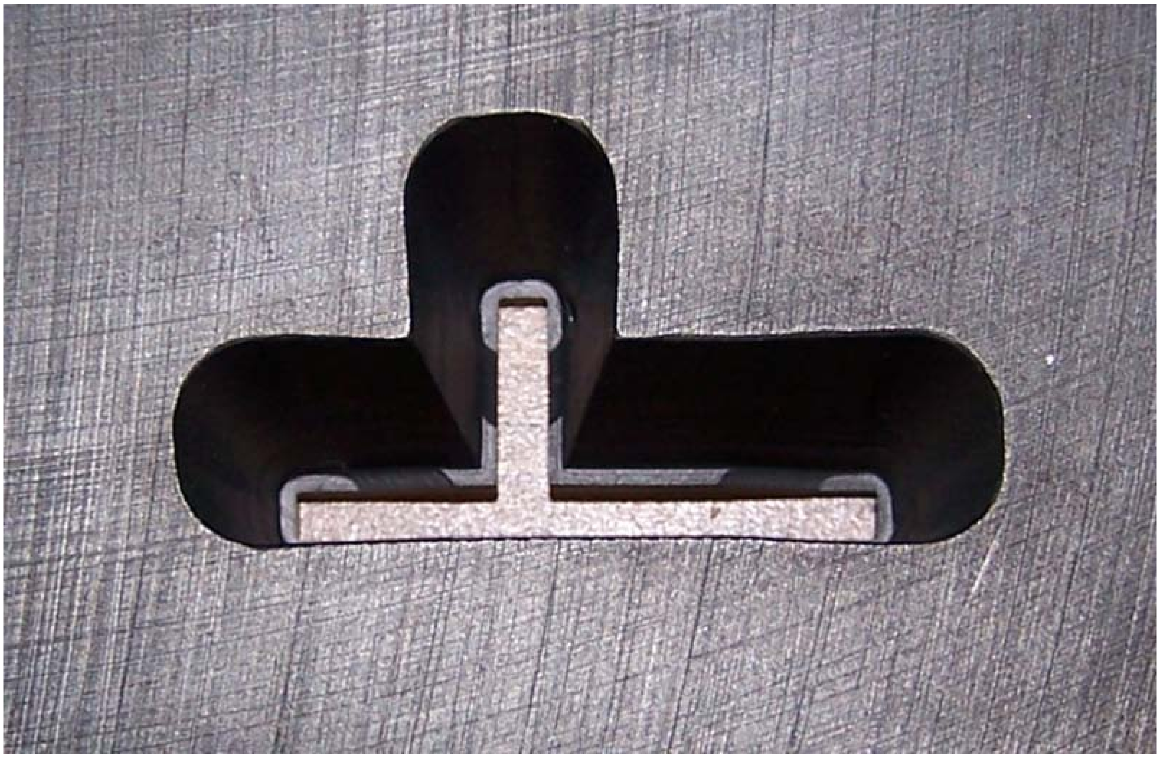
Hot extrusion temperature for various metals

Material	Temperature [°C (°F)]
Magnesium	350-450 (650-850)
Aluminium	350-500 (650-900)
Copper	600-1100 (1200-2000)
Steel	1200-1300 (2200–2400)
Titanium	700-1200 (1300-2100)
Nickel	1000-1200 (1900–2200)
Refractory alloys	up to 2000 (4000)

The extrusion process is generally economical when producing between several kilograms (pounds) and many tons, depending on the material being extruded. There is a crossover point where roll forming becomes more economical. For instance, some steels become more economical to roll if producing more than 20,000 kg (50,000 lb).

Aluminium hot extrusion die

Front side of a four family die. For reference, the die is 228 mm (9.0 in) in diameter.



Close up of the shape cut into the die. Notice that the walls are drafted and that the back wall thickness varies.

Back side of die. The wall thickness of the extrusion is 3 mm (0.12 in).

Cold extrusion

Cold extrusion is done at room temperature or near room temperature. The advantages of this over hot extrusion are the lack of oxidation, higher strength due to cold working, closer tolerances, good surface finish, and fast extrusion speeds if the material is subject to hot shortness.

Materials that are commonly cold extruded include: lead, tin, aluminum, copper, zirconium, titanium, molybdenum, beryllium, vanadium, niobium, and steel.

Examples of products produced by this process are: collapsible tubes, fire extinguisher cases, shock absorber cylinders, automotive pistons, and gear blanks.

Warm extrusion

Warm extrusion is done above room temperature, but below the recrystallization temperature of the material the temperatures ranges from 800 to 1800 °F (424 to 975 °C). It is usually used to achieve the proper balance of required forces, ductility and final extrusion properties.

Equipment

A horizontal hydraulic press for hot aluminum extrusion (loose dies and scrap visible in foreground)

There are many different variations of extrusion equipment. They vary by four major characteristics:

1. Movement of the extrusion with relation to the ram. If the die is held stationary and the ram moves towards it then its called "direct extrusion". If the ram is held stationary and the die moves towards the ram its called "indirect extrusion".
2. The position of the press, either vertical or horizontal.
3. The type of drive, either hydraulic or mechanical.
4. The type of load applied, either conventional (variable) or hydrostatic.

A single or twin screw auger, powered by an electric motor, or a ram, driven by hydraulic pressure (often used for steel and titanium alloys), oil pressure (for aluminum), or in other specialized processes such as rollers inside a perforated drum for the production of many simultaneous streams of material.

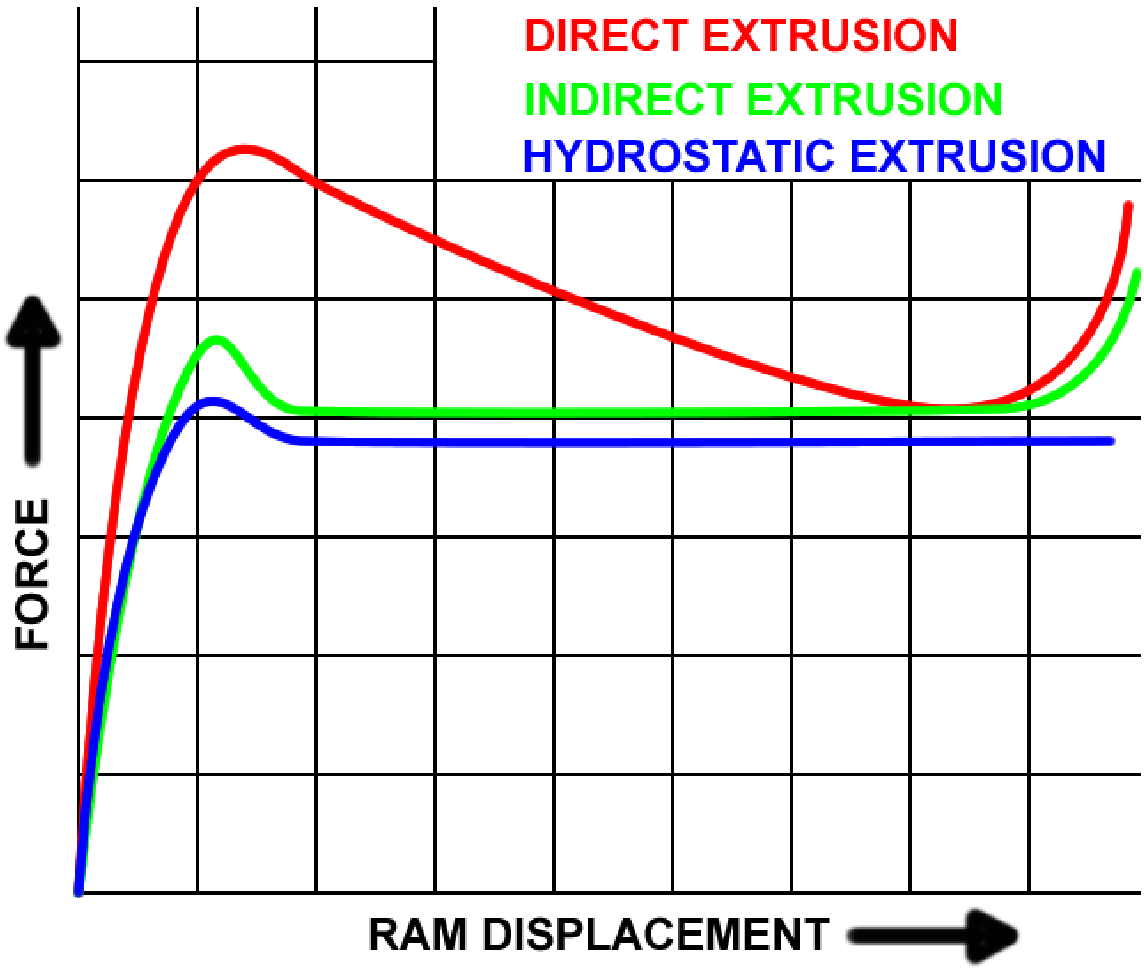
Typical extrusion presses cost more than $100,000, whereas dies can cost up to $2000.

Forming internal cavities

Two-piece aluminum extrusion die set (parts shown separated.) The male part (at right) is for forming the internal cavity in the resulting round tube extrusion.

There are several methods for forming internal cavities in extrusions. One way is to use a hollow billet and then use a fixed or floating mandrel. A fixed mandrel, also known as a German type, means it is integrated into the dummy block and stem. A floating mandrel, also known as a French type, floats in slots in the dummy block and aligns itself in the die when extruding. If a solid billet is used as the feed material then it must first be pierced by the mandrel before extruding through the die. A special press is used in order to control the mandrel independently from the ram. The solid billet could also be used with a spider die, porthole die or bridge die. All of these types of dies incorporate the mandrel in the die and have "legs" that hold the mandrel in place. During extrusion the metal divides and flows around the legs, leaving weld lines in the final product.

Direct extrusion



Plot of forces required by various extrusion processes.

Direct extrusion, also known as forward extrusion, is the most common extrusion process. It works by placing the billet in a heavy walled container. The billet is pushed through the die by a ram or screw. There is a reusable dummy block between the ram and the billet to keep them separated. The major disadvantage of this process is that the force required to extrude the billet is greater than that need in the indirect extrusion process because of the frictional forces introduced by the need for the billet to travel the entire length of the container. Because of this the greatest force required is at the beginning of process and slowly decreases as the billet is used up. At the end of the billet the force greatly increases because the billet is thin and the material must flow radially to exit the die. The end of the billet (called the butt end) is not used for this reason.

Indirect extrusion

In indirect extrusion, also known as backwards extrusion, the billet and container move together while the die is stationary. The die is held in place by a "stem" which has to be longer than the container length. The maximum length of the extrusion is ultimately dictated by the column strength of the stem. Because the billet moves with the container the frictional forces are eliminated. This leads to the following advantages:

- A 25 to 30% reduction of friction, which allows for extruding larger billets, increasing speed, and an increased ability to extrude smaller cross-sections
- There is less of a tendency for extrusions to crack because there is no heat formed from friction
- The container liner will last longer due to less wear
- The billet is used more uniformly so extrusion defects and coarse grained peripherals zones are less likely.

The disadvantages are:

- Impurities and defects on the surface of the billet affect the surface of the extrusion. These defects ruin the piece if it needs to be anodized or the aesthetics are important. In order to get around this the billets may be wire brushed, machined or chemically cleaned before being used.
- This process isn't as versatile as direct extrusions because the cross-sectional area is limited by the maximum size of the stem.

Hydrostatic extrusion

In the hydrostatic extrusion process the billet is completely surrounded by a pressurized liquid, except where the billet contacts the die. This process can be done hot, warm, or cold, however the temperature is limited by the stability of the fluid used. The process must be carried out in a sealed cylinder to contain the hydrostatic medium. The fluid can be pressurized two ways:

1. *Constant-rate extrusion*: A ram or plunger is used to pressurize the fluid inside the container.
2. *Constant-pressure extrusion*: A pump is used, possibly with a pressure intensifier, to pressurize the fluid, which is then pumped to the container.

The advantages of this process include:

- No friction between the container and the billet reduces force requirements. This ultimately allows for faster speeds, higher reduction ratios, and lower billet temperatures.
- Usually the ductility of the material increases when high pressures are applied.
- An even flow of material.
- Large billets and large cross-sections can be extruded.

- No billet residue is left on the container walls.

The disadvantages are:

- The billets must be prepared by tapering one end to match the die entry angle. This is needed to form a seal at the beginning of the cycle. Usually the entire billet needs to be machined to remove any surface defects.
- Containing the fluid under high pressures can be difficult.

Drives

Most modern direct or indirect extrusion presses are hydraulically driven, but there are some small mechanical presses still used. Of the hydraulic presses there are two types: direct-drive oil presses and accumulator water drives.

Direct-drive oil presses are the most common because they are reliable and robust. They can deliver over 35 MPa (5000 psi). They supply a constant pressure throughout the whole billet. The disadvantage is that they are slow, between 50 and 200 mm/s (2–8 ips).

Accumulator water drives are more expensive and larger than direct-drive oil presses, and they lose about 10% of their pressure over the stroke, but they are much faster, up to 380 mm/s (15 ips). Because of this they are used when extruding steel. They are also used on materials that must be heated to very hot temperatures for safety reasons.

Hydrostatic extrusion presses usually use castor oil at pressure up to 1400 MPa (200 ksi). Castor oil is used because it has good lubricity and high pressure properties.

Extrusion defects

- Surface cracking - When the surface of an extrusion splits. This is often caused by the extrusion temperature, friction, or speed being too high. It can also happen at lower temperatures if the extruded product temporarily sticks to the die.
- Pipe - A flow pattern that draws the surface oxides and impurities to the center of the product. Such a pattern is often caused by high friction or cooling of the outer regions of the billet.
- Internal cracking - When the center of the extrusion develops cracks or voids. These cracks are attributed to a state of hydrostatic tensile stress at the centerline in the deformation zone in the die. (A similar situation to the necked region in a tensile stress specimen)
- Surface lines - When there are lines visible on the surface of the extruded profile. This depends heavily on the quality of the die production and how well the die is maintained, as some residues of the material extruded can stick to the die surface and produce the embossed lines.

Materials

Metal

Metals that are commonly extruded include:

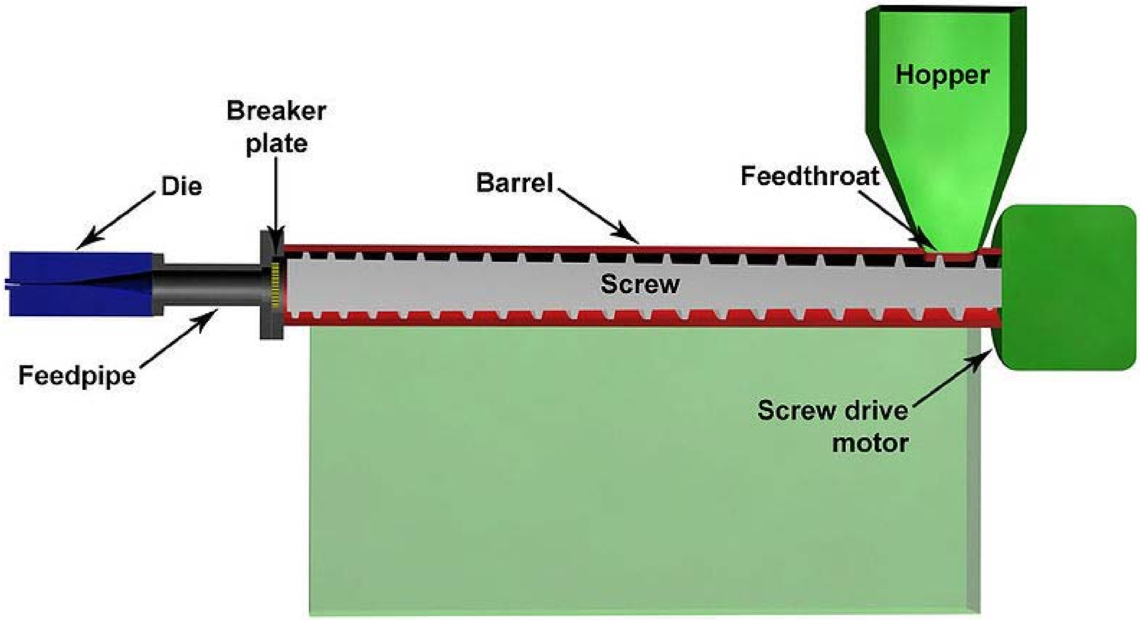
- **Aluminium** is the most commonly extruded material. Aluminium can be hot or cold extruded. If it is hot extruded it is heated to 575 to 1100 °F (300 to 600 °C). Examples of products include profiles for tracks, frames, rails, mullions, and heat sinks.
- **Copper** (1100 to 1825 °F (600 to 1000 °C)) pipe, wire, rods, bars, tubes, and welding electrodes. Often more than 100 ksi (690 MPa) is required to extrude copper.
- **Lead** and **tin** (maximum 575 °F (300 °C)) pipes, wire, tubes, and cable sheathing. Molten lead may also be used in place of billets on vertical extrusion presses.
- **Magnesium** (575 to 1100 °F (300 to 600 °C)) aircraft parts and nuclear industry parts. Magnesium is about as extrudable as aluminum.
- **Zinc** (400 to 650 °F (200 to 350 °C)) rods, bar, tubes, hardware components, fitting, and handrails.
- **Steel** (1825 to 2375 °F (1000 to 1300 °C)) rods and tracks. Usually plain carbon steel is extruded, but alloy steel and stainless steel can also be extruded.
- **Titanium** (1100 to 1825 °F (600 to 1000 °C)) aircraft components including seat tracks, engine rings, and other structural parts.

Magnesium and aluminium alloys usually have a 0.75 μm (30 μin) RMS or better surface finish. Titanium and steel can achieve a 3 micrometres (120 μin) RMS.

In 1950, Ugine Séjournet, of France, invented a process which uses glass as a lubricant for extruding steel. The Ugine-Sejournet, or Sejournet, process is now used for other materials that have melting temperatures higher than steel or that require a narrow range of temperatures to extrude. The process starts by heating the materials to the extruding temperature and then rolling it in glass powder. The glass melts and forms a thin film, 20 to 30 mils (0.5 to 0.75 mm), in order to separate it from chamber walls and allow it to act as a lubricant. A thick solid glass ring that is 0.25 to 0.75 in (6 to 18 mm) thick is placed in the chamber on the die to lubricate the extrusion as it is forced through the die. A second advantage of this glass ring is its ability to insulate the heat of the billet from the die. The extrusion will have a 1 mil thick layer of glass, which can be easily removed once it cools.

Another breakthrough in lubrication is the use of phosphate coatings. With this process, in conjunction with glass lubrication, steel can be cold extruded. The phosphate coat absorbs the liquid glass to offer even better lubricating properties.

Plastic



Sectional view of a plastic extruder showing the components

Plastics extrusion commonly uses plastic chips or pellets, which are usually dried in a hopper before going to the feed screw. The polymer resin is heated to molten state by a combination of heating elements and shear heating from the extrusion screw. The screw forces the resin through a die, forming the resin into the desired shape. The extrudate is cooled and solidified as it is pulled through the die or water tank. In some cases (such as fibre-reinforced tubes) the extrudate is pulled through a very long die, in a process called pultrusion.

A multitude of polymers are used in the production of plastic tubing, pipes, rods, rails, seals, and sheets or films.

Ceramic

Ceramic can also be formed into shapes via extrusion. Terracotta extrusion is used to produce pipes. Many modern bricks are also manufactured using a brick extrusion process.

Food

Macaroni is an extruded hollow pasta.

Extrusion has found great application in food processing. Products such as pastas, breakfast cereals, Fig Newtons, cookie dough, Murukku, Sevai, Idiappam, jalebi, french fries, baby food, dry pet food and ready-to-eat snacks are mostly manufactured by extrusion. In the extrusion process, raw materials are first ground to the correct particle size (usually the consistency of coarse flour). The dry mix is passed through a pre-conditioner, where other ingredients are added (liquid sugar, fats, dyes, meats and water depending on the product being made), steam is also injected to start the cooking process. The preconditioned mix is then passed through an extruder, and then forced through a die where it is cut to the desired length. The cooking process takes place within the extruder where the product produces its own friction and heat due to the pressure generated (10–20 bar). The cooking process utilizes a process known as starch gelatinization. Extruders using this process have a capacity from 1–25 tonnes per hour depending on design.

Use of the extrusion cooking process gives the following food benefits:

- Starch gelatinization
- Protein denaturation
- Inactivation of raw food enzymes

- Destruction of naturally occurring toxins
- Diminishing of microorganisms in the final product

Extrusion is also used to modify starch and to pellet animal feed.

Drug carriers

Extrusion through nano-porous, polymeric filters is being used to manufacture suspensions of lipid vesicles liposomes or Transfersomes for use in pharmaceutical products. The anti-cancer drug Doxorubicin in liposome delivery system is formulated by extrusion, for example.

Biomass briquettes

The extrusion production technology of fuel briquettes is the process of extrusion screw wastes (straw, sunflower husks, buckwheat, etc.) or finely shredded wood waste (sawdust) under high pressure when heated from 160 to 350 °C. The resulting fuel briquettes do not include any of the binders, but one natural - the lignin contained in the cells of plant wastes. The temperature during compression, causes melting of the surface of bricks, making it more solid, which is important for the transportation of briquettes.

Design

The design of an extrusion profile has a large impact on how readily it can be extruded. The maximum size for an extrusion is determined by finding the smallest circle that will fit around the cross-section, this is called the *circumscribing circle*. This diameter, in turn, controls the size of the die required, which ultimately determines if the part will fit in a given press. For example, a larger press can handle 60 cm (24 in) diameter circumscribing circles for aluminium and 55 cm (22 in). diameter circles for steel and titanium.

The complexity of an extruded profile can be roughly quantified by calculating the *shape factor*, which is the amount of surface area generated per unit mass of extrusion. This affects the cost of tooling as well as the rate of production.

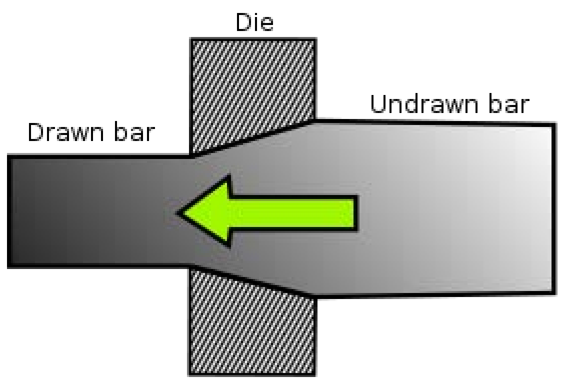
Thicker sections generally need an increased section size. In order for the material to flow properly legs should not be more than ten times longer than their thickness. If the cross-section is asymmetrical, adjacent sections should be as close to the same size as possible. Sharp corners should be avoided; for aluminium and magnesium the minimum radius should be 0.4 mm (1/64 in) and for steel corners should be 0.75 mm (0.030 in) and fillets should be 3 mm (0.12 in). The following table lists the minimum cross-section and thickness for various materials.

Material	Minimum cross-section [cm^2 (sq. in.)]	Minimum thickness [mm (in.)]
Carbon steels	2.5 (0.40)	3.00 (0.120)
Stainless steel	3.0-4.5 (0.45-0.70)	3.00-4.75 (0.120-0.187)
Titanium	3.0 (0.50)	3.80 (0.150)
Aluminium	<2.5 (0.40)	1.00 (0.040)
Magnesium	<2.5 (0.40)	1.00 (0.040)

Chapter-7

Drawing (Manufacturing) and Deep Drawing

Drawing



The basic drawing process for a wire, bar or tube.

Drawing is a metalworking process which uses tensile forces to stretch metal. It is broken up into two types: sheet metal drawing and wire, bar, and tube drawing. The specific definition for sheet metal drawing is that it involves plastic deformation over a curved axis. For wire, bar, and tube drawing the starting stock is drawn through a die to reduce its diameter and increase its length. Drawing is usually done at room temperature, thus classified a cold working process, however it may be performed at elevated temperatures to hot work large wires, rods or hollow sections in order to reduce forces.

Processes

Sheet metal

The success of forming is in relation to two things, the flow and stretch of material. As a die forms a shape from a flat sheet of metal, there is a need for the material to move into the shape of the die. The flow of material is controlled through pressure applied to the blank and lubrication applied to the die or the blank. If the form moves too easily, wrinkles will occur in the part. To correct this, more pressure or less lubrication is applied to the blank to limit the flow of material and cause the material to stretch or thin. If too much pressure is applied, the part will become too thin and break. Drawing metal is the science of finding the correct balance between wrinkles and breaking to achieve a successful part.

Deep drawing

Sheet metal drawing becomes *deep drawing* when the workpiece is drawing longer than its diameter. It is common that the workpiece is also processed using other forming processes, such as piercing, ironing, necking, rolling, and beading.

Bar, tube & wire

Bar, tube, and wire drawing all work upon the same principle: the starting stock drawn through a die to reduce the diameter and increase the length. Usually the die is mounted on a draw bench. The end of the workpiece is reduced or pointed to get the end through the die. The end is then placed in grips and the rest of the workpiece is pulled through the die. Steels, copper alloys, and aluminium alloys are common materials that are drawn.

Drawing can also be used to produce a cold formed shaped cross-section. Cold drawn cross-sections are more precise and have a better surface finish than hot extruded parts. Inexpensive materials can be used instead of expensive alloys for strength requirements, due to work hardening.

Bar drawing

Bars or rods that are drawn cannot be coiled therefore straight-pull draw benches are used. Chain drives are used to draw workpieces up to 30 m (98 ft). Hydraulic cylinders are used for shorter length workpieces.

The reduction in area is usually restricted to 20 to 50%, because greater reductions would exceed the tensile strength of the material, depending on its ductility. To achieve a certain size or shape multiple passes through progressively smaller dies or intermediate anneals may be required.

Tube drawing

Tube drawing is very similar to bar drawing, except the beginning stock is a tube. It is used to decrease the diameter, improve surface finish and improve dimensional accuracy. A mandrel may or may not be used depending on the specific process used.

Wire drawing

This technique has long been used to produce flexible metal wire by drawing the material through a series of dies of decreasing size. These dies are manufactured from a number of materials, the most common being tungsten carbide and diamond.

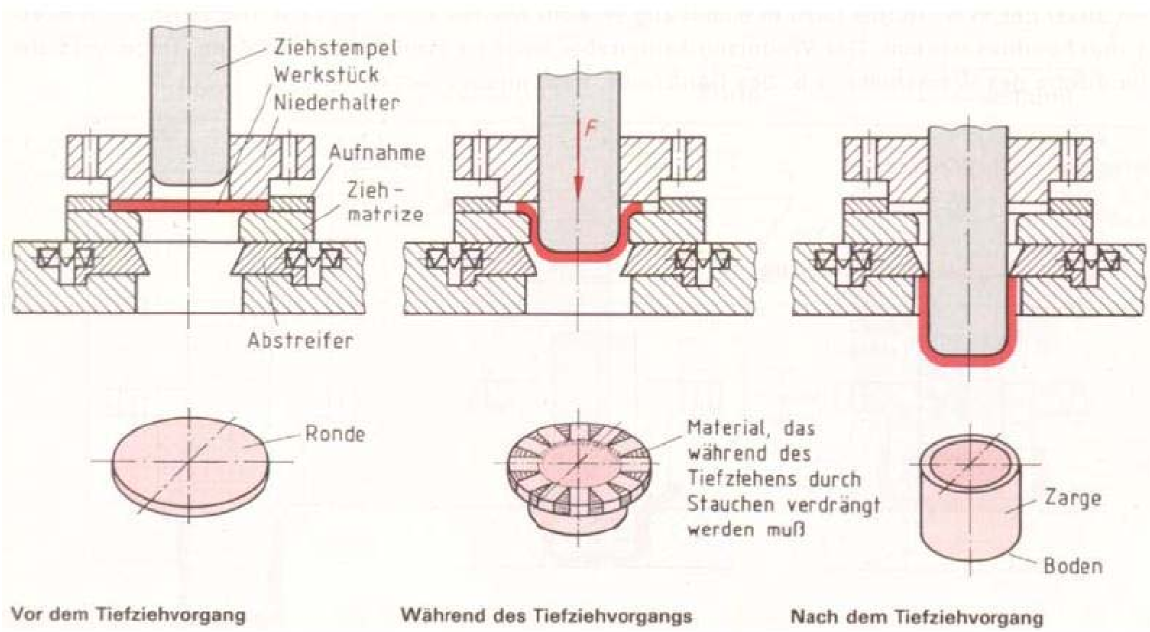
Plastic drawing

Plastic drawing, sometimes referred to as *cold drawing*, is the same process as used on metal bars, but applied to plastics.

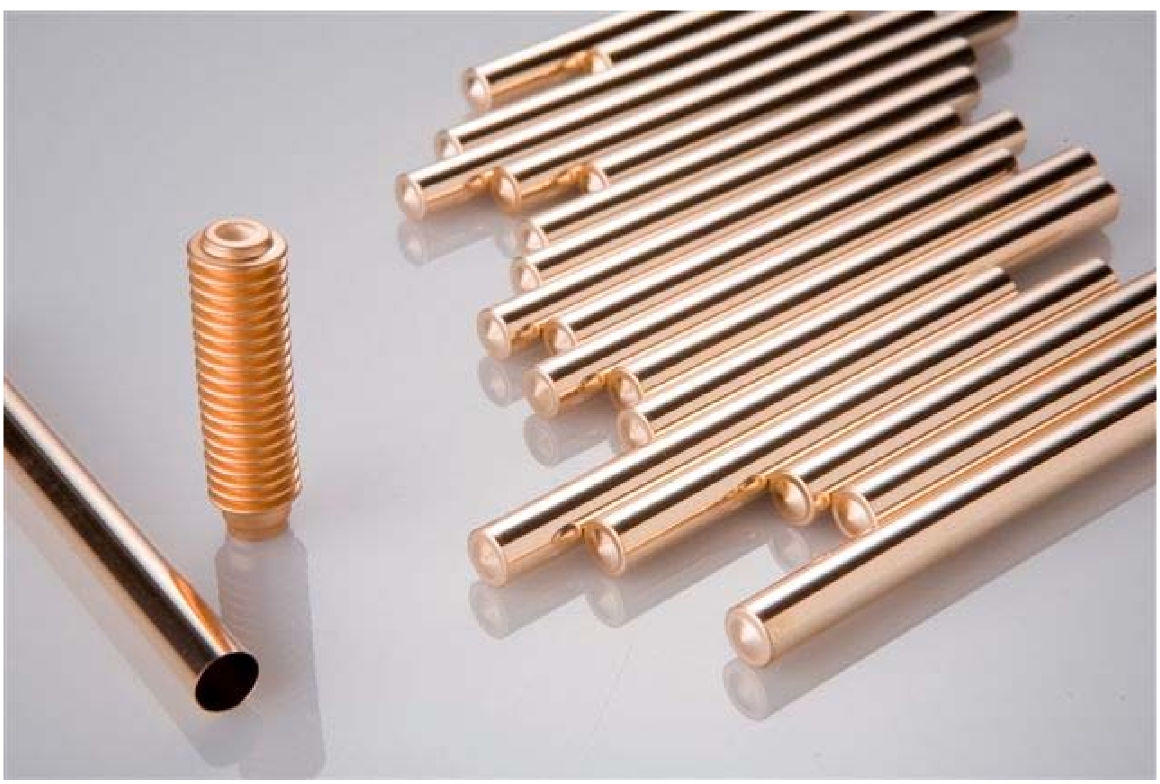
Cold drawing is primarily used in manufacturing plastic fibers. The process was discovered by Julian Hill in 1930 while trying to make fibers from an early polyester. It is performed after the material has been "spun" into filaments; by extruding the polymer melt through pores of a spinneret. During this process, the individual polymer chains tend to somewhat align because of viscous flow. These filaments still have an amorphous structure, so they are drawn to align the fibers further, thus increasing crystallinity, tensile strength and stiffness. This is done on a draw twister machine.

For nylon, the fiber is stretched four times its spun length. The crystals formed during drawing are held together by hydrogen bonds between the amide hydrogens of one chain and the carbonyl oxygens of another chain.

Deep drawing



An illustration of deep drawing, annotated in German.



Example of deep drawn part

Deep drawing is a sheet metal forming process in which a sheet metal blank is radially drawn into a forming die by the mechanical action of a punch. It is thus a shape transformation process with material retention. The process is considered "deep" drawing when the depth of the drawn part exceeds its diameter. This is achieved by redrawing the part through a series of dies. The flange region (sheet metal in the die shoulder area) experiences a radial drawing stress and a tangential compressive stress due to the material retention property. These compressive stresses (hoop stresses) result in flange wrinkles (wrinkles of the first order). Wrinkles can be prevented by using a blank holder, the function of which is to facilitate controlled material flow into the die radius.

Process

The total drawing load consists of the ideal forming load and an additional component to compensate for friction in the contacting areas of the flange region and bending forces at the die radius. The forming load is transferred from the punch radius through the drawn part wall into the deformation region (sheet metal flange). Due to tensile forces acting in the part wall, wall thinning is prominent and results in an uneven part wall thickness. It can be observed that the part wall thickness is lowest at the point where the part wall loses contact with the punch, i.e. at the punch radius. The thinnest part thickness determines the maximum stress that can be transferred to the deformation zone. Due to material volume constancy, the flange thickens and results in blank holder contact at the outer boundary rather than on the entire surface. The maximum stress that can be safely transferred from the punch to the blank sets a limit on the maximum blank size (initial blank diameter in the case of rotationally symmetrical blanks). An indicator of material formability is the limiting drawing ratio (LDR), defined as the ratio of the maximum blank diameter that can be safely drawn into a cup without flange to the punch diameter. Determination of the LDR for complex components is difficult and hence the part is inspected for critical areas for which an approximation is possible. During severe deep drawing the material work hardens and it may be necessary to anneal the parts in controlled atmosphere ovens to restore the original elasticity of the material.

Commercial applications of this metal shaping process often involve complex geometries with straight sides and radii. In such a case, the term stamping is used in order to distinguish between the deep drawing (radial tension-tangential compression) and stretch-and-bend (along the straight sides) components. Deep drawing is always accompanied by other forming techniques within the press. These other forming methods include trimming, piercing, bulging, reducing, ironing (wall thickness reduction), rolling or beading (often to create O-ring seats), threading, sidewall piercing, crimping, date or pattern stamping and many others.It common use to consider this process as a cost saving alternative to turned parts which require much more raw material.

For high precision mass productions, it is always advisable to use a transfer press also known as eyelet press. The advantage of this type of press, in respect to conventional progressive presses, is that the parts is transferred from one die to the next by means of so called "fingers". Not only do the fingers transfer the parts but they also guide the component during the process. This allows parts to be drawn to the deepest depths with the tightest tolerances.

Variations

Deep drawing has been classified into *conventional* and *unconventional* deep drawing. The main aim of any unconventional deep drawing process is to extend the formability limits of the process. Some of the unconventional processes include hydromechanical deep drawing, Hydroform process, Aquadraw process, Guerin process, Marform process and the hydraulic deep drawing process to name a few.

The Marform process, for example, operates using the principle of rubber pad forming techniques. Deep-recessed parts with either vertical or slopped walls can be formed. In this type of forming, the die rig employs a rubber pad as one tool half and a solid tool half, similar to the die in a conventional die set, to form a component into its final shape. Dies are made of cast light alloys and the rubber pad is 1.5-2 times thicker than the component to be formed. For Marforming, single-action presses are equipped with die cushions and blank holders. The blank is held against the rubber pad by a blank holder, through which a punch is acting as in conventional deep drawing. It is a double-acting apparatus: at first the ram slides down, then the blank holder moves: this feature allows it to perform deep drawings (30-40% transverse dimension) with no wrinkles.

Industrial uses of deep drawing processes include automotive body and structural parts, aircraft components, utensils and white goods. Complex parts are normally formed using progressive dies in a single forming press or by using a press line.

Workpiece materials and power requirements

Softer materials are much easier to deform and therefore require less force to draw. The following is a table demonstrating the draw force to percent reduction of commonly used materials.

Drawing force required for various materials and reductions [kN]

Material	**Percent reduction**			
	39%	**43%**	**47%**	**50%**
Aluminium	88	101	113	126
Brass	117	134	151	168
Cold-rolled steel	127	145	163	181
Stainless steel	166	190	214	238

Tool materials

Punches and dies are typically made of tool steel, however carbon steel is cheaper, but not as hard and is therefore used in less severe applications, it is also common to see cemented carbides used where high wear and abrasive resistance is present. Alloy steels are normally used for the ejector system to kick the part out and in durable and heat resistant blankholders.

Lubrication and cooling

Lubricants are used to reduce friction between the working material and the punch and die. They also aid in removing the part from the punch. Some examples of lubricants used in drawing operations are heavy-duty emulsions, phosphates, white lead, and wax films. Plastic films covering both sides of the part while used with a lubricant will leave the part with a fine surface.

Chapter-8

Shear Forming & Hemming and Seaming

Shear forming

Fig. 1. A shear formed product: a hollow cone with a thin wall thickness

Shear forming, also referred as **shear spinning**, is similar to metal spinning. In **shear spinning** the area of the final piece is approximately equal to that of the flat sheet metal blank. The wall thickness is maintained by controlling the gap between the roller and the mandrel. In **shear forming** a reduction of the wall thickness occurs.

Before the 1950s, spinning was performed on a simple turning lathe. When new technologies were introduced to the field of metal spinning and powered dedicated spinning machines were available, shear forming started its development in Sweden.

Schematics

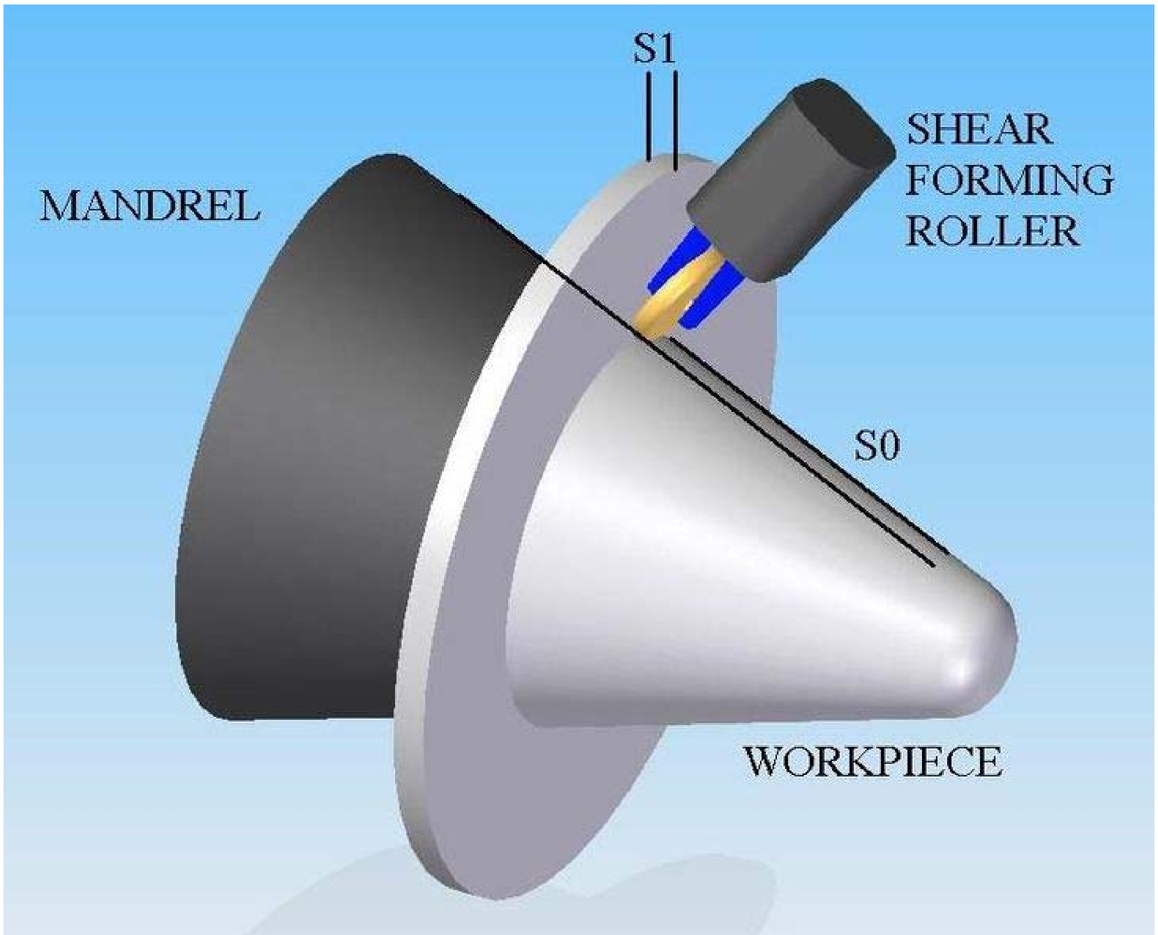


Fig. 2. Shear forming schematics

Figure 2 shows the schematics of a shear forming process.

1. A sheet metal blank is placed between the mandrel and the chuck of the spinning machine. The mandrel has the interior shape of the desired final component.

2. A roller makes the sheet metal wrap the mandrel so that it takes its shape.

As can be seen, s1 which is the initial wall thickness of the workpiece is reduced to s0.

Workpiece and roller tool profiles

In shear forming, the starting workpiece can have circular or rectangular cross sections. On the other hand, the profile shape of the final component can be concave, convex or a combination of these two.

A shear forming machine will look very much like a conventional spinning machine, except for that it has to be much more robust to withstand the higher forces necessary to perform the shearing operation.

The design of the roller must be considered carefully, because it affects the shape of the component, the wall thickness, and dimensional accuracy. The smaller the tool nose radius, the higher the stresses and poorest thickness uniformity achieved.

Spinnability

Spinnability, sometimes referred as **shear spinnability**, can be defined as the ability of a metal to undergo shear spinning deformation without exceeding its tensile strength and tearing. Published work on spinnability is available from the authors Kegg and Kalpakcioglu.

Kegg predicted that for materials with a tensile reduction of 80%, the limiting spinning reduction will be equal or greater than 80%. Kalpakciouglu concluded that for metals with a true fracture strain of 0.5 or greater, there is a maximum limit for the shear forming reduction. For materials with a true strain below 0.5, the spinnability depends on the ductility of the material.

Highly spinnable materials include ductile materials like aluminum and certain steel alloys.

Importance of shear forming operations in manufacturing

Shear forming and conventional spinning are being used less than other manufacturing processes such as deep drawing and ironing. Being able to achieve almost net shape, thin sectioned parts, makes spinning a versatile process used widely in the production of lightweight items. Other advantages of shear spinning include the good mechanical properties of the final item and a very good surface finish.

Typical components produced by mechanically powered spinning machines include rocket nose cones, gas turbine engine and dish aerials.

Flow forming

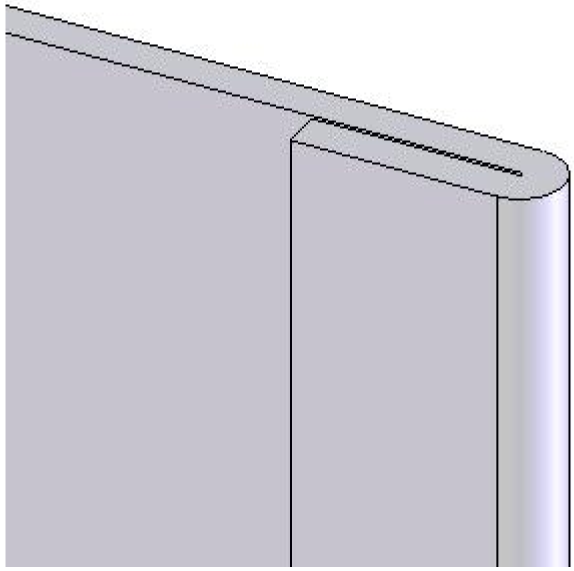
Flow Forming is an incremental metal forming technique in which a disk or tube of metal is formed over a mandrel by one or more rollers using tremendous pressure. The roller deforms the workpiece, forcing it against the mandrel, both axially lengthening and radially thinning it. Since the pressure exerted by the roller is highly localized and the material is incrementally formed, often there is a net savings in energy in forming over drawing or ironing processes. However, these savings are often not realized because of the inherent difficulties in predicting the resulting deformation for a given roller path. Flow forming subjects the workpiece to a great deal of friction and deformation. These two factors may heat the workpiece to several hundred degrees if proper cooling fluid is not utilized.

Flow forming is often used to manufacture automobile wheels and can be used to draw a wheel to net width from a machined blank.

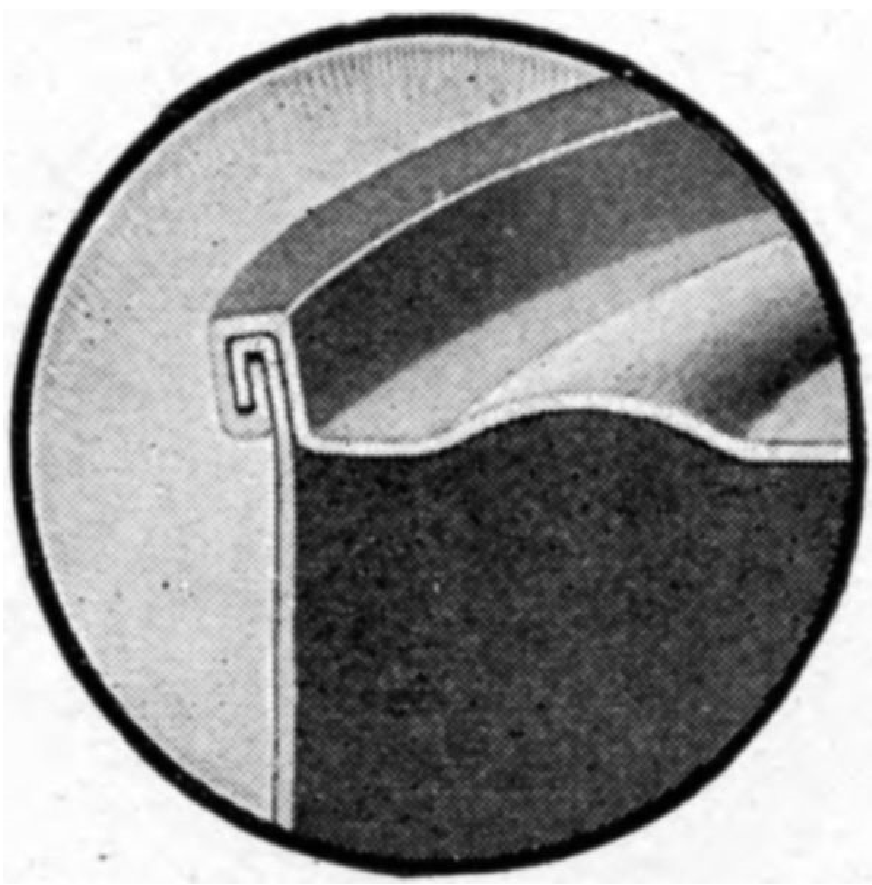
During flow forming, the workpiece is cold worked, changing its mechanical properties, so its strength becomes similar to that of forged metal.

Hemming and seaming

hemming process



A closed hem



A seam

Hemming and **seaming** are two similar metalworking processes in which a sheet metal edge is rolled over onto itself. A hem is when the edge is rolled flush to itself, while a seam joins the edges of two materials.

Hems are commonly used to reinforce an edge, hide burrs and rough edges, and improve appearance.

Seams are commonly used in the food industry on canned goods, on amusement park cars, and in the automotive industry.

Process

The process for both hemming and seaming are the same, except that the tonnage requirement is greater for seaming. The process starts by bending the edge to an acute angle. A flattening die is then used flatten the hem.

Types

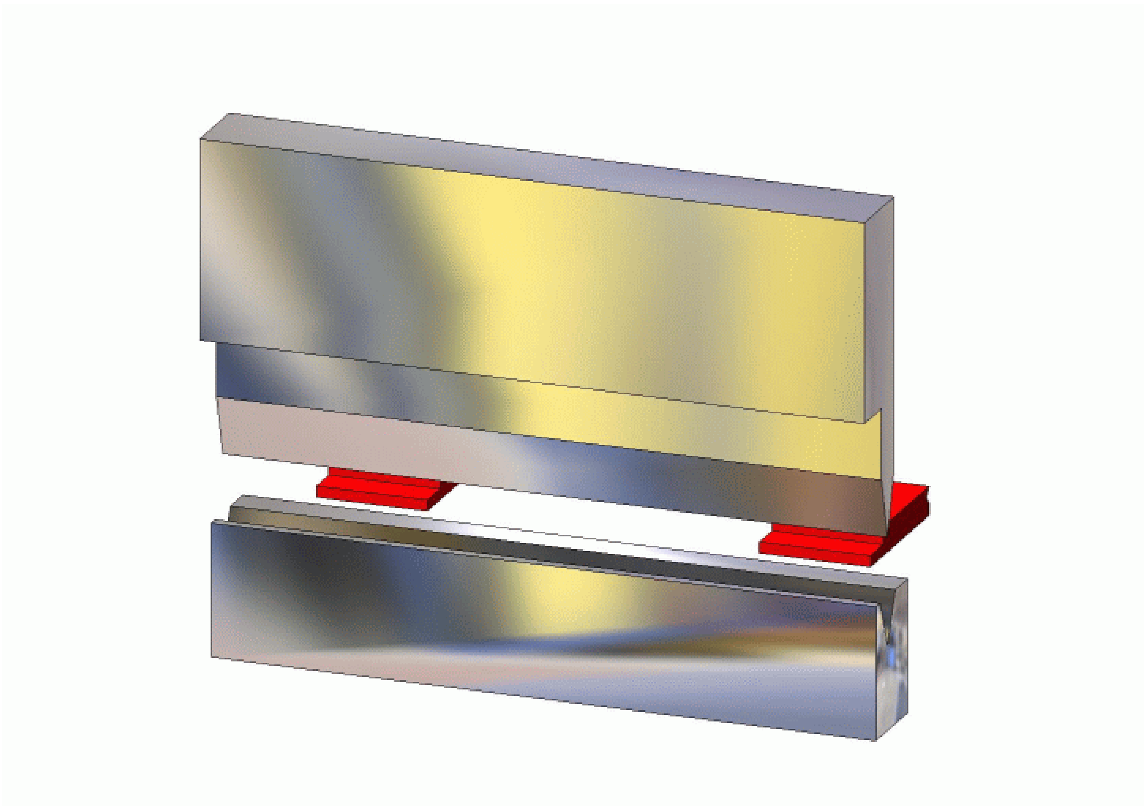
There are two types of hemmed edges: *closed hems* and *open hems*. Closed hems are completely flush while open hems have an air pocket in the bend. The major difference is that the tonnage required for a closed hem is much greater than that for an open hem.

Tons per meter requirement for hemming cold-rolled steel and stainless steel

Material thickness [mm]	Open hem	Closed hem
0.6	9	23
0.8	12	32
1.0	15	40
1.2	17	50
1.6	24	63
2.0	30	80
2.6	55	90
3.2	70	100
4.5	105	200

Chapter-9

Bending (Metalworking)

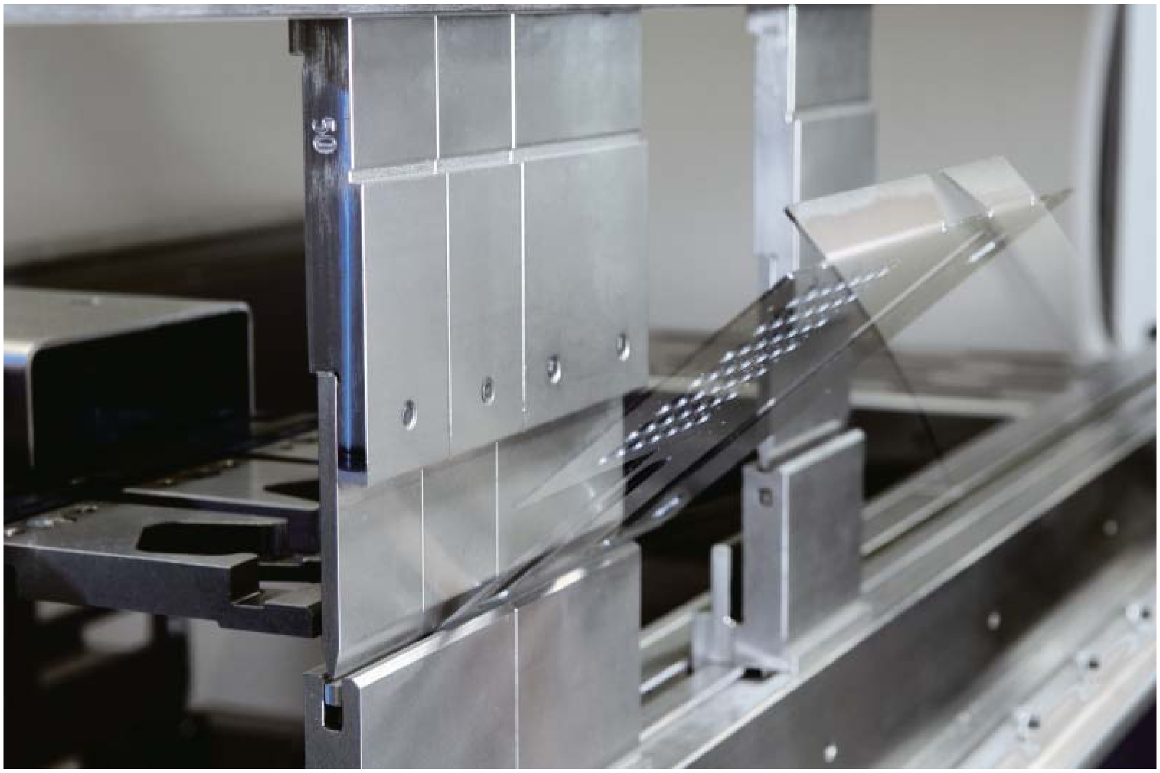


Bending

Press brake

Bending is a manufacturing process that produces a V-shape, U-shape, or channel shape along a straight axis in ductile materials, most commonly sheet metal. Commonly used equipment include box and pan brakes, brake presses, and other specialized machine presses. Typical products that are made like this are boxes such as electrical enclosures and rectangular ductwork.

Process

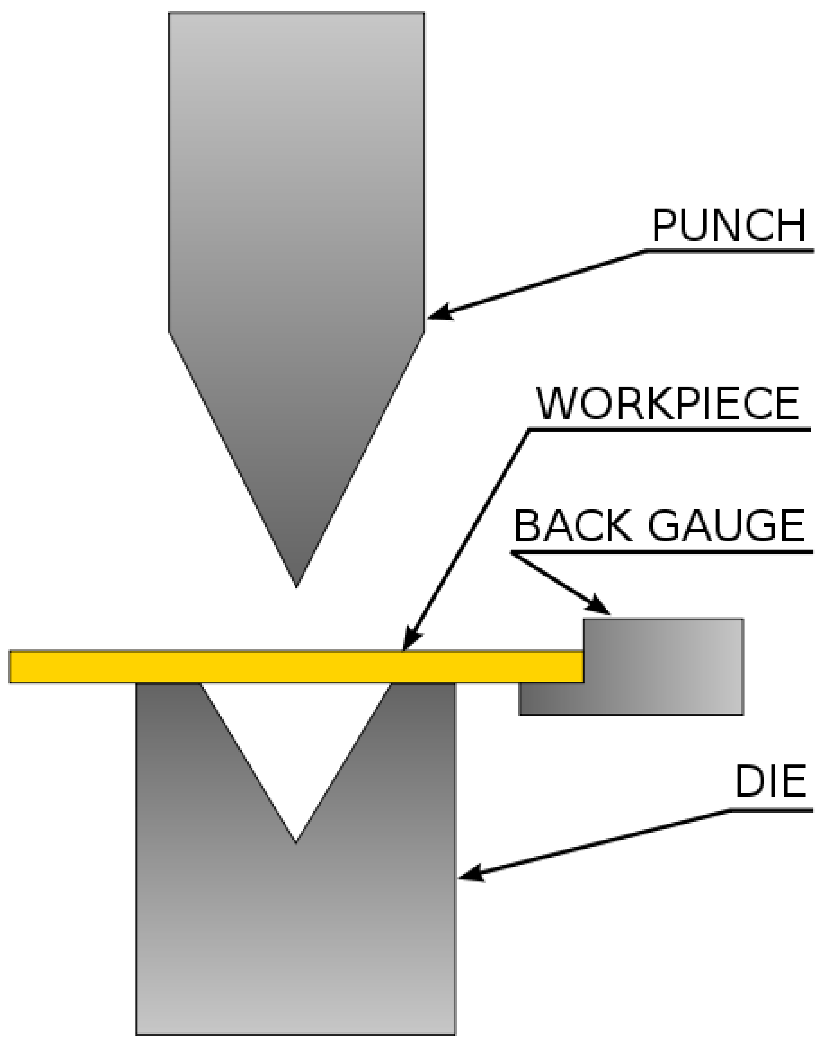


Bending process

In press brake forming, a work piece is positioned over the die block and the die block presses the sheet to form a shape. Usually bending has to overcome both tensile stresses as well as compressive stresses. When bending is done, the residual stresses cause the material to *spring back* towards its original position, so the sheet must be over-bent to achieve the proper bend angle. The amount of springback is dependent on the material, and the type of forming. When sheet metal is bent, it stretches in length. The *bend deduction* is the amount the sheet metal will stretch when bent as measured from the outside edges of the bend. The *bend radius* refers to the inside radius. The formed bend radius is dependent upon the dies used, the material properties, and the material thickness.

The U-punch forms a U-shape with a single punch.

Types



A schematic of air bending with a backgauge.

There are three basic types of bending on a press brake, each is defined by the relationship of the end tool position to the thickness of the material. These three are Air Bending, Bottoming and Coining. The configuration of the tools for these three types of bending are nearly identical. A die with a long rail form tool with a radiused tip that locates the inside profile of the bend is called a punch. Punches are usually attached to the ram of the machine by clamps and move to produce the bending force. A die with a long rail form tool that has concave or V shaped lengthwise channel that locate the outside profile of the form is called a die. Dies are usually stationary and located under the material on the bed of the machine. Note that some locations do not differentiate between the two different kinds of dies (punches and dies.) The other types of bending listed use specially designed tools or machines to perform the work.

Air bending

This bending method forms material by pressing a punch (also called the upper or top die) into the material, forcing it into a bottom V-die, which is mounted on the press. The punch forms the bend so that the distance between the punch and the side wall of the V is greater than the material thickness (T).

Either a V-shaped or square opening may be used in the bottom die (dies are frequently referred to as tools or tooling). A set of top and bottom dies are made for each product or part produced on the press. Because it requires less bend force, air bending tends to use smaller tools than other methods.

Some of the newer bottom tools are adjustable, so, by using a single set of top and bottom tools and varying press-stroke depth, different profiles and products can be produced. Different materials and thicknesses can be bent in varying bend angles, adding the advantage of flexibility to air bending. There are also fewer tool changes, thus, higher productivity.

A disadvantage of air bending is that, because the sheet does not stay in full contact with the dies, it is not as precise as some other methods, and stroke depth must be kept very accurate. Variations in the thickness of the material and wear on the tools can result in defects in parts produced.

Air bending's angle accuracy is approximately ±0.5 deg. Angle accuracy is ensured by applying a value to the width of the V opening, ranging from 6 T (six times material thickness) for sheets to 3 mm thick to 12 T for sheets more than 10 mm thick. Springback depends on material properties, influencing the resulting bend angle.

Depending on material properties, the sheet may be overbended to compensate for springback.

Air bending does not require the bottom tool to have the same radius as the punch. Bend radius is determined by material elasticity rather than tool shape.

The flexibility and relatively low tonnage required by air bending are helping to make it a popular choice. Quality problems associated with this method are countered by angle-measuring systems, clamps and crowning systems adjustable along the x and y axes, and wear-resistant tools.

The K-Factor approximations given below are more likely to be accurate for air bending than the other types of bending due to the lower forces involved in the forming process.

Bottoming

In bottoming, the sheet is forced against the V opening in the bottom tool. U-shaped openings cannot be used. Space is left between the sheet and the bottom of the V opening. The optimum width of the V opening is 6 T (T stands for material thickness) for sheets about 3 mm thick, up to about 12 T for 12 mm thick sheets. The bending radius for must be at least 0.8 T to 2 T for sheet steel. Larger bend radii require about the same force as larger radii in air bending, however, smaller radii require greater force—up to five times as much—than air bending. Advantages of bottoming include greater accuracy and less springback. A disadvantage is that a different tool set is needed for each bend angle, sheet thickness, and material. In general, air bending is the preferred technique.

Coining

In coining, the top tool forces the material into the bottom die with five to 30 times the force of air bending, causing permanent deformation through the sheet. There is little, if any, springback. Coining can produce an inside radius is as low as 0.4 T, with a 5 T width of the V opening. While coining can attain high precision, higher costs mean that it is not often used.

Three-point bending

Three-point bending is a newer process that uses a die with an adjustable-height bottom tool, moved by a servo motor. The height can be set within 0.01 mm. Adjustments between the ram and the upper tool are made using a hydraulic cushion, which accommodates deviations in sheet thickness. Three-point bending can achieve bend angles with 0.25 deg. precision. While three-point bending permits high flexibility and precision, it also entails high costs and there are fewer tools readily available. It is being used mostly in high-value niche markets.

Folding

In folding, clamping beams hold the longer side of the sheet. The beam rises and folds the sheet around a bend profile. The bend beam can move the sheet up or down, permitting the fabricating of parts with positive and negative bend angles. The resulting bend angle is influenced by the folding angle of the beam, tool geometry, and material properties. Large sheets can be handled in this process, making the operation easily automated. There is little risk of surface damage to the sheet.

Wiping

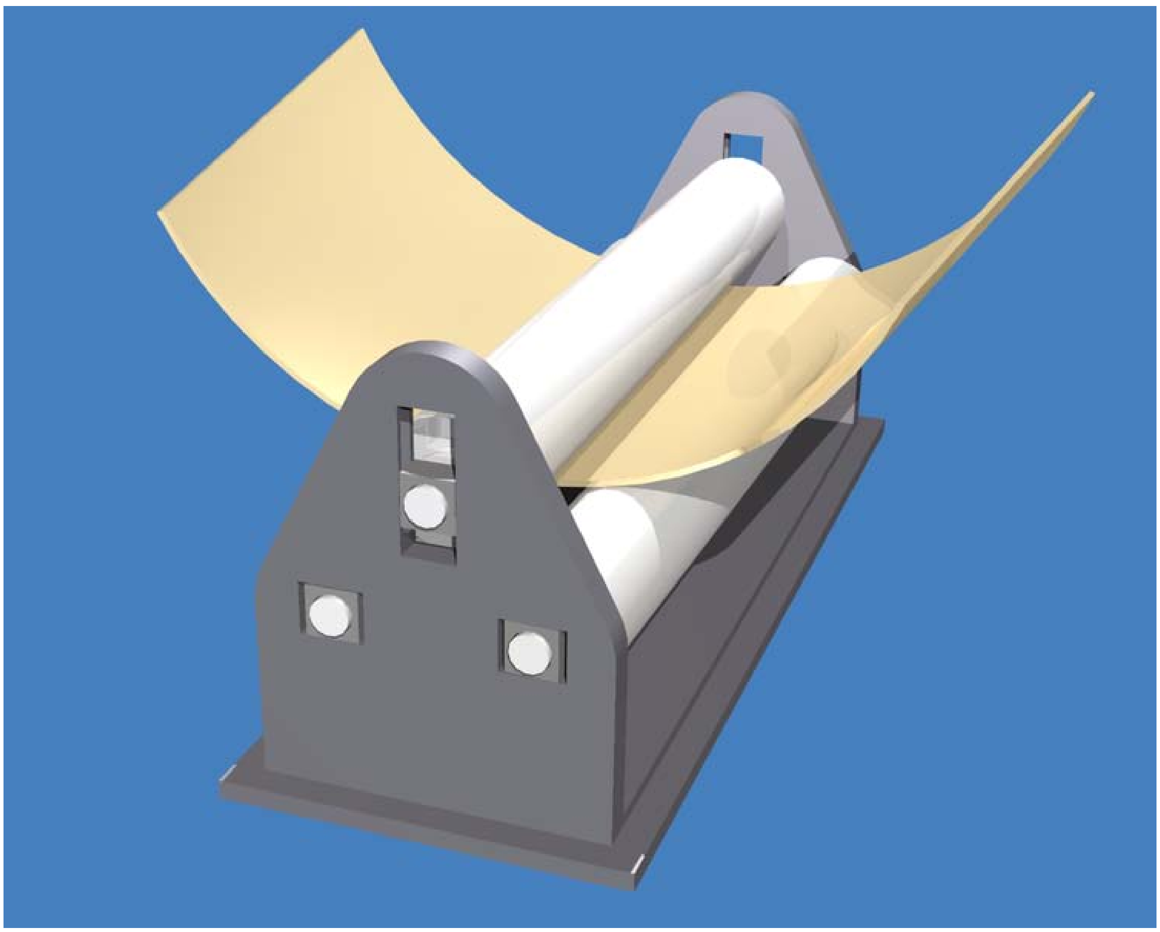
In wiping, the longest end of the sheet is clamped, then the tool moves up and down, bending the sheet around the bend profile. Though faster than folding, wiping has a higher risk of producing scratches or otherwise damaging the sheet, because the tool is moving over the sheet surface. The risk increases if sharp angles are being produced. Wiping on press brakes involves special tools.

This method will typically bottom or coin the material to set the edge to help overcome springback. In this bending method, the radius of the bottom die determines the final bend radius.

Rotary bending

Rotary bending is similar to wiping but the top die is made of a freely rotating cylinder with the final formed shape cut into it and a matching bottom die. On contact with the sheet, the roll contacts on two points and it rotates as the forming process bends the sheet. This bending method is typically considered a "non-marking" forming process suitable to pre-painted or easily marred surfaces. This bending process can produce angles greater than 90° in a single hit on standard press brakes or flat presses.

Roll bending



Roll bending

The roll bending process induces a curve into bar or plate workpieces.

Elastomer bending

In this method, the bottom V-die is replaced by a flat pad of urethane or rubber. As the punch forms the part, the urethane deflects and allows the material to form around the punch. This bending method has a number of advantages. The urethane will wrap the material around the punch and the end bend radius will be very close to the actual radius on the punch. It provides a non-marring bend and is suitable for pre-painted or sensitive materials. Using a special punch called a *radius ruler* with relieved areas on the urethane U-bends greater than 180° can be achieved in one hit, something that is not possible with conventional press tooling. Urethane tooling should be considered a consumable item and while they are not cheap , they are a fraction of the cost of dedicated steel tooling. It also has some drawbacks, this method requires tonnage similar to bottoming and coining and does not do well on flanges that are irregular in shape, that is where the edge of the bent flange is not parallel to the bend and is short enough to engage the urethane pad.

Joggling

A joggle bend in sheet metal and a joggling tool

Joggling, also known as **joggle bending**, is an offset bending process in which the two opposite bends are each greater than 90°, and are separated by a neutral web less than 5 workpiece thicknesses apart.

Joggle bends are commonly used on complex airframe parts because it reduces modeling time from days to hours. They also increase strength, hardness, and possibly resistance to wear.

Calculations

Many variations of these formulas exist and are readily available online. These variations may often seem to be at odds with one another, but they are invariably the same formulas simplified or combined. What is presented here are the unsimplified formulas. All formulas use the following keys:

- BA = bend allowance
- BD = bend deduction
- R = inside bend radius
- K = K-Factor, which is t / T
- T = material thickness
- t = distance from inside face to the neutral line
- A = bend angle in degrees (the angle through which the material is bent)

The *neutral line* (also called the *neutral axis*) is an imaginary line that can be drawn through the cross-section of the workpiece that represents the lack of any internal forces. Its location in the material is a function of the forces used to form the part and the material yield and tensile strengths.

Both bend deduction and bend allowance represent the difference between the neutral line or unbent *flat pattern* (the required length of the material prior to bending) and the formed bend. Subtracting them from the combined length of both flanges gives the flat pattern length. The question of which formula to use is determined by the dimensioning method used to define the flanges as shown in the two diagrams below.

Bend allowance

The *bend allowance* (BA) is the length of the arc of the neutral line between the tangent points of a bend in any material. Adding the length of each flange taken between the center of the radius to the BA gives the Flat Pattern length. This bend allowance formula is used to determine the flat pattern length when a bend is dimensioned from 1) the center of the radius, 2) a tangent point of the radius or 3) the outside tangent point of the radius on an acute angle bend.

The BA can be calculated using the following formula:

$$BA = A\left(\frac{\pi}{180}\right)(R + K \times T)$$

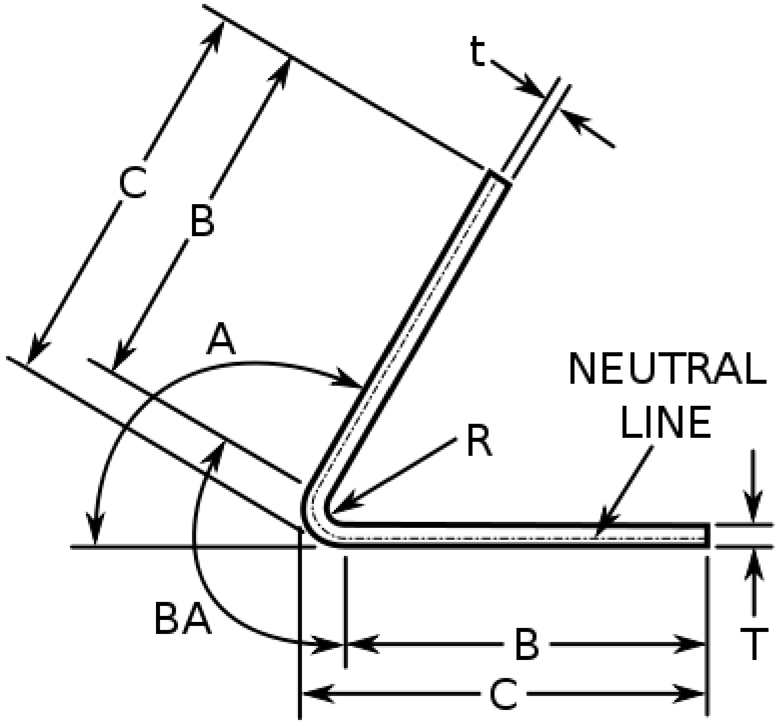


Diagram showing standard dimensioning scheme when using Bend Allowance formulas.
Note that when dimensions "C" are specified, dimension B = C - R - T

Bend deduction

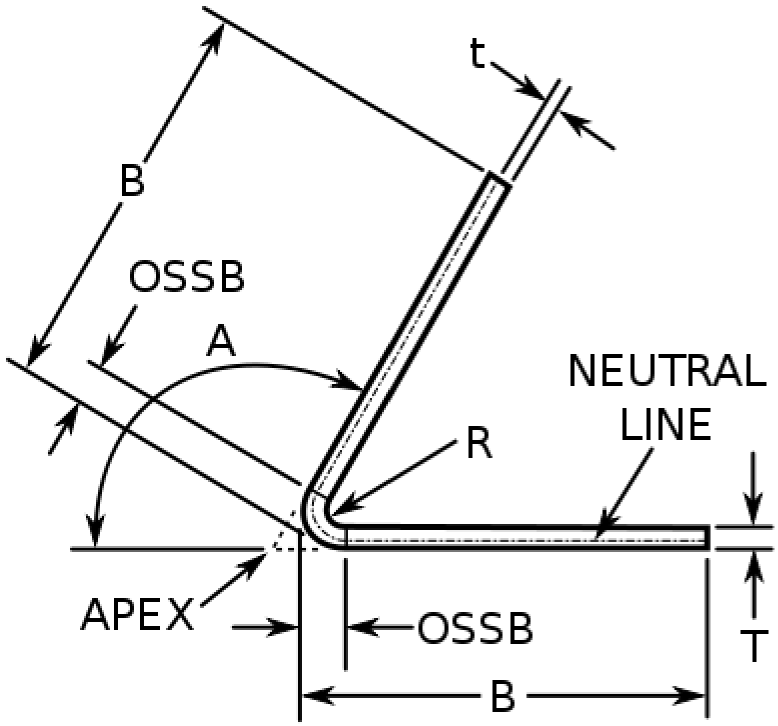


Diagram showing standard dimensioning scheme when using Bend Deduction formulas.

The *outside set back* (OSSB) is the length from the tangent point of the radius to the apex of the outside of the bend. The *bend deduction* (BD) is twice the outside setback minus the bend allowance. Most sheet metal drawings use this kind of dimensioning because it is offers more precise control over the flange lengths (compared to dimensioning it to the outside tangent of the radius) by removing any variations in the formed radius from the measurement. Because of this, the BD calculation is used more often than BA alone. BD is calculated using the following formula:

$$BD = 2\,(R + T)\tan\frac{A}{2} - BA$$

K-factor

K-factor is a ratio of material thickness to the location of the neutral line as defined by t/T where t = location of the neutral line and T = material thickness. The K-Factor formulation does not take the forming stresses into account but is simply a geometric calculation of the location of the neutral line after the forces are applied and is thus the roll-up of all the unknown (error) factors for a given setup. The K-factor depends on many factors including the material, the type of bending operation (coining, bottoming, air-bending, etc.) the tools, etc. and is typically between 0.3 to 0.5.

The following equation relates the K-factor to the bend allowance:

$$K = \frac{-R + \frac{BA}{\pi A/180}}{T}$$

The following table is a "Rule of Thumb". Actual results may vary remarkably.

Generic K-Factors	**Aluminum**		**Steel**
Radius	**Soft Materials**	**Medium Materials**	**Hard Materials**
Air Bending			
0 to Thickness	0.33	0.38	0.40
Thickness to 3 x Thickness	0.40	0.43	0.45
Greater than 3 x Thickness	0.50	0.50	0.50
Bottoming			
0 to Thickness	0.42	0.44	0.46
Thickness to 3 x Thickness	0.46	0.47	0.48
Greater than 3 x Thickness	0.50	0.50	0.50
Coining			
0 to Thickness	0.38	0.41	0.44
Thickness to 3 x Thickness	0.44	0.46	0.47
Greater than 3 x Thickness	0.50	0.50	0.50

The following formula can be used in place of the table as a good *approximation* of the K-Factor for Air Bending:

LOG(MIN(100,MAX(20 × R,T) / T)) / LOG(100) / 2

Material considerations

Material sheet thickness varies from 1/32 to ½ in with length from 6 in to 20 ft. Ductile materials are best suited for the pressing like aluminum, mild steel and new plastic materials.

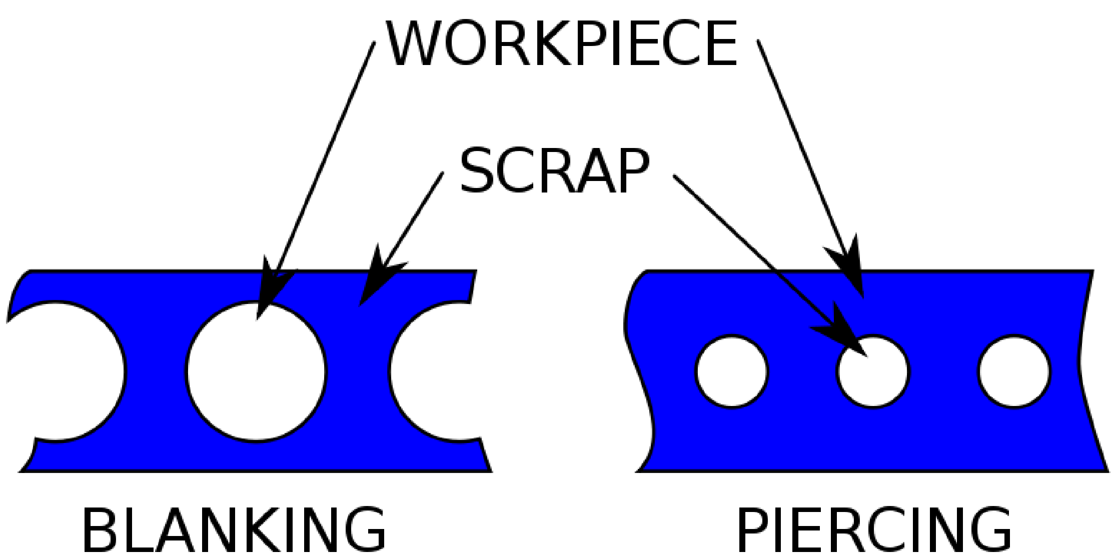
Advantages

Bending is a cost effective process when used for low to medium quantities, because it does not require significant amounts of tooling.

Chapter-10

Blanking and Piercing & Electroforming

Blanking and piercing



Blanking versus piercing

Blanking and **piercing** are shearing processes in which a punch and die are used to modify webs. The tooling and processes are the same between the two, only the terminology is different: in blanking the punched out piece is used and called a *blank*; in piercing the punched out piece is scrap.

Types

There are various types of blanking and piercing: lancing, perforating, notching, nibbling, shaving, cutoff, and dinking.

Lancing

Lancing is a piercing operation in which the workpiece is sheared and bent with one strike of the die. A key part of this process is that there is not reduction of material, only a modification in its geometry. This operation is used to make tabs, vents, and louvers.

The cut made in lancing is not a closed cut, like in perforation even though a similar machine is used, but a side is left connected to be bent sharply or in more of a rounded manner.

Lancing can be used to make partial contours and free up material for other operations further down the production line. Along with these reasons lancing is also used to make tabs (where the material is bent at a 90 degree angle to the material), vents (where the bend is around 45 degrees), and louvers (where the piece is rounded or cupped).

Normally lancing is done on a mechanical press, lancing requires the use of punches and dies to be used. The different punches and dies determine the shape and angle (or curvature) of the newly made section of the material. The dies and punches are needed to be made of tool steel to withstand the repetitious nature of the procedure.

Perforating

Perforating is a piercing operation that involves punching a large number of closely spaced holes.

Notching

Notching is a piercing operation that removes material from the edge of the workpiece.

Nibbling

The nibbling process cuts a contour by producing a series of overlapping slits or notches. This allows for complex shapes to be formed in sheet metal up to 6 mm (0.25 in) thick using simple tools. The nibbler is essentially a small punch and die that reciprocates quickly; around 300–900 times per minute. Punches are available in various shape and sizes; oblong and rectangular punches are common because they minimize waste and allow for greater distances between strokes, as compared to a round punch. Nibbling can occur on the exterior or interior of the material, however interior cuts require a hole to insert the tool.

The process is often used on parts that do not have quantities that can justify a dedicated blanking die. The edge smoothness is determined by the shape of the cutting die and the amount the cuts overlap; naturally the more the cuts overlap the cleaner the edge. For added accuracy and smoothness most shapes created by nibbling undergo filing or grinding processes after completion.

Shaving

The shaving process is a finishing operation where a small amount of metal is sheared away from an already blanked part. Its main purpose is to obtain better dimensional accuracy, but secondary purposes include squaring the edge and smoothing the edge. Blanked parts can be shaved to an accuracy of up to 0.025 mm (0.001 in).

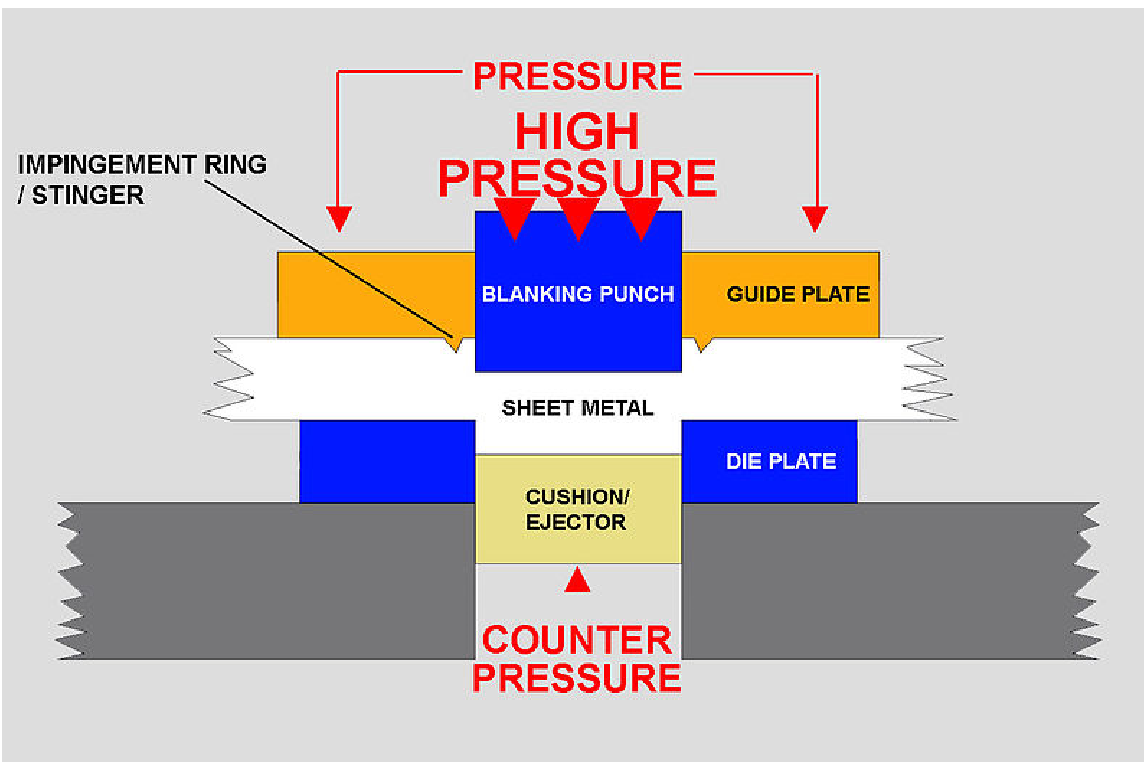
Trimming

The trimming operation is the last operation performed because it cuts away excess or unwanted irregular features from the workpiece.

Cutoff

The cutoff process is used to separate a stamping or other product from a strip or stock. This operation is very common with progressive die sequences. The cutoff operation often produces the periphery counter to the workpiece.

Fine blanking



Typical fine blanking press cross section

Fine blanking is a specialized form of blanking where there is no fracture zone when shearing. This is achieved by compressing the whole part and then an upper and lower punch extract the blank. This allows the process to hold very tight tolerances, and perhaps eliminate secondary operations.

Materials that can be fine blanked include aluminium, brass, copper, and carbon, alloy and stainless steels.

Fine blanking presses are similar to other metal stamping presses, but they have a few critical additional parts. A typical compound fine blanking press includes a hardened die punch (male), the hardened blanking die (female), and a guide plate of similar shape/size to the blanking die. The guide plate is the first applied to the material, impinging the material with a sharp protrusion or *stinger* around the perimeter of the die opening. Next a counter pressure is applied opposite the punch, and finally the die punch forces the material through the die opening. Since the guide plate holds the material so tightly, and since the counter pressure is applied, the material is cut in a manner more like extrusion than typical punching. Mechanical properties of the cut benefit similarly with a hardened layer at the cut edge from the cold working of the part. Because the material is so tightly held and controlled in this setup, part flatness remains very true, distortion is nearly eliminated, and edge burr is minimal. Clearances between the die and punch are generally around 1% of the cut material thickness, which typically varies between 0.5–13 mm (0.020–0.51 in). Currently parts as thick as 19 mm (0.75 in) can be cut using fine blanking. Tolerances between ±0.0003–0.002 in (0.0076–0.051 mm) are possible based on material thickness & tensile strength, and part layout.

With standard compound fine blanking processes, multiple parts can often be completed in a single operation. Parts can be pierced, partially pierced, offset (up to 75°), embossed, or coined, often in a single operation. Some combinations may require progressive fine blanking operations, in which multiple operations are performed at the same pressing station.

The advantages of fine blanking are:

- excellent dimensional control, accuracy, and repeatability through a production run.
- excellent part flatness is retained.
- straight, superior finished edges to other metal stamping processes.
- smaller holes possible relative to thickness of material.
- little need to machine details.
- multiple features can be added simultaneously in 1 operation.
- more economical for large production runs than traditional operations when additional machining cost and time are factored in (1000–20000 parts minimum, depending on secondary machining operations)

The disadvantages are:

- slightly higher tooling cost when compared to traditional punching operations.
- slightly slower than traditional punching operations.

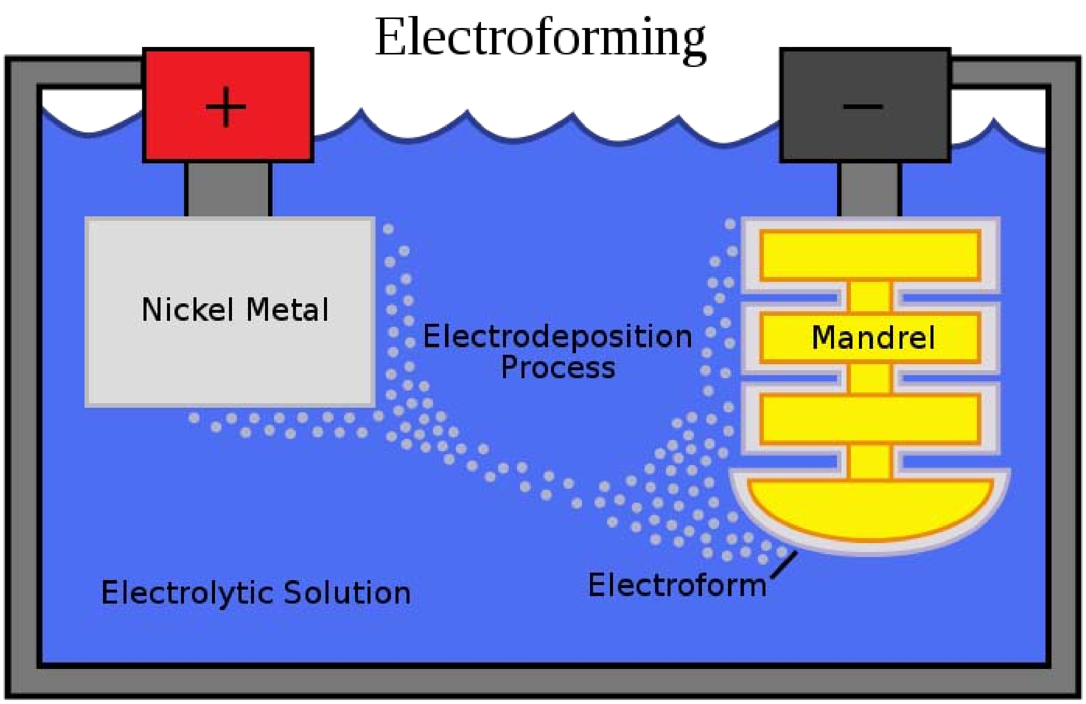
Tooling

The amount of clearance between a punch and die for piercing is governed by the thickness and strength of the workpiece material being pierced. The punch-die clearance determines the load or pressure experienced at the cutting edge of the tool, commonly known as point pressure. Excessive point pressure can lead to accelerated wear and ultimately failure.

Burr height is typically used as an index to measure tool wear, because it is easy to measure during production.

A simple operation may only need a pancake die. While many dies perform complex procedures simultaneously, a pancake die may only perform one simple procedure with the finished product being removed by hand.

Electroforming



Electroforming process

Electroforming is a metal forming process that forms thin parts through the electroplating process. The part is produced by plating a metal skin onto a base form, known as a mandrel, which is removed after plating. This process differs from electroplating in that the plating is much thicker and can exist as a self-supporting structure when the mandrel is removed.

In recent years, due to its ability to replicate a mandrel surface precisely atom-by-atom with practically no loss of fidelity, electroforming has taken on new importance in the fabrication of micro and nano scale metallic devices and in producing precision injection molds with micro and nano scale feature for production of nonmetallic micromolded objects.

Process

In the basic electroforming process, an electrolytic bath is used to deposit nickel or other electroplatable metal onto a conductive patterned surface, such as glass or stainless steel. Once the plated material has been built up to the desired thickness, the electroformed part is stripped off the master substrate. This process allows high-quality duplication of the master and therefore permits quality production—at low unit costs with high repeatability and excellent process control.

The mandrel is made of a non-conductive material it can be covered with a conductive coating. Technically, it is a process of synthesizing a metal object by controlling the electrodeposition of metal passing through an electrolytic solution onto a metal or metalized form.

The object being electroformed can be a permanent part of the end product or can be temporary (as in the case of wax), and removed later, leaving only the metal form, the "electroform". New technologies have made it possible for mandrels to be very complex. In order to facilitate the removal of the electroform from the mandrel, a mandrel is often made of aluminum. Because aluminum can easily be chemically dissolved, a complex electroform can be produced with near exactness.

Advantages and disadvantages

The main advantage of electroforming is that it reproduces the external shape of the mandrel within one micrometre. Generally, forming an internal cavity accurately is more difficult than forming an external shape, however the opposite holds true for electroforming because the mandrel's exterior can be accurately machined.

Compared to other basic metal forming processes (casting, forging, stamping, deep drawing, machining and fabricating) electroforming is very effective when requirements call for extreme tolerances, complexity or light weight. The precision and resolution inherent in the photographically produced conductive patterned substrate, allows finer geometries to be produced to tighter tolerances while maintaining superior edge definition with a near optical finish. Electroformed metal is extremely pure, with superior properties over wrought metal due to its refined crystal structure. Multiple layers of electroformed metal can be molecularly bonded together, or to different substrate materials to produce complex structures with "grown-on" flanges and bosses.

Tolerances of 1.5 to 3 nanometres have been reported.

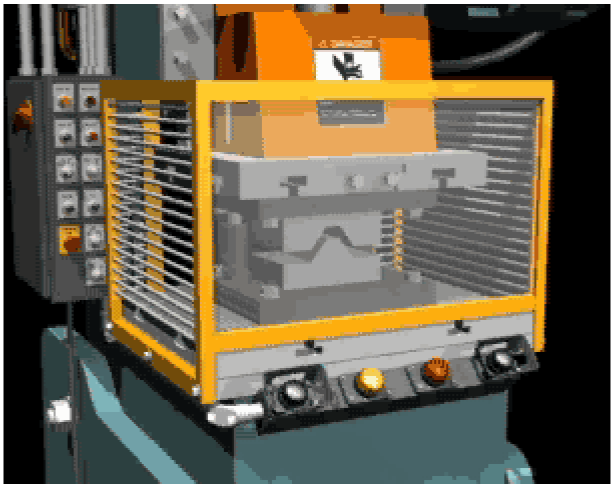
A wide variety of shapes and sizes can be made by electroforming, the principal limitation being the need to strip the product from the mandrel. Since the fabrication of a product requires only a single pattern or mandrel, low production quantities can be made economically.

Chapter-11

Machine Press and Forming Limit Diagram

Machine press

Manual goldsmith press



Power press with a fixed barrier guard

A **machine press**, commonly shortened to **press**, is a machine tool that changes the shape of a workpiece.

Types

- Pneumatic press
- Knuckle-joint press

Drives

Servomechanism

A servomechanism press, also known as a *servo press* or a '*electro press*, is a press driven by an AC servo motor. The torque produced is converted to a linear force via a ball screw. Pressure and position are controlled though a load cell and an encoder. The main advantage of a servo press is its low energy consumption; its only 10-20% of other press machines. Another advantage is a quiet and clean work environment.

Shop press

A simple frame, fabricated from steel, containing a bottle jack or simple hydraulic cylinder. Good for general-purpose work in the auto mechanic shop, machine shop, garage or basement shops, etc. Typically 1 to 30 tons of pressure, depending on size and expense. Classed with engine hoists and engine stands in many tool catalogs.

Forging press

A forging press reforms the work piece into a three dimensional object—not only changing its visible shape but also the internal structure of the material. A stronger part results from this process than if the object was machined.

Press brake

Press brake

A press brake is a special type of machine press that bends sheet metal into shape. A good example of the type of work a press brake can do is the backplate of a computer case. Other examples include brackets, frame pieces and electronic enclosures just to name a few. Some press brakes have CNC controls and can form parts with accuracy to a fraction of a millimetre. Bending forces can exceed 4,000 kilonewtons (900,000 lbf).

Punch press

A punch press is used to form holes.

Rolling press

A *rolling press* has a set of rollers used to thin sheet metal. The sheet metal is fed into the rollers, which are turning, and the sheet is pulled through. The space between the rollers is smaller than the starting sheet metal thickness, therefore the metal is made thinner and/or wider.

Screw press

A screw press is also known as a fly press.

Stamping press

A stamping press is a machine press used to shape or cut metal by deforming it with a die. It generally consists of a press frame, a bolster plate, and a ram.

Others

Another kind of press is a set of plates with a relief, or depth-based design, in them. The metal is placed between the plates, and the plates are pressed up against each other, deforming the metal in the desired fashion. This may be coining or embossing or forming.

Capping presses form caps from rolls of aluminium foil at up to 660 per minute.

History

Historically, metal was shaped by hand using a hammer. Later, larger hammers were constructed to press more metal at once, or to press thicker materials. Often a smith would employ a helper or apprentice to swing the sledgehammer while the smith concentrated on positioning the workpiece. Adding windmill or steam power yielded still larger hammers such as steam hammers. Most modern machine presses use a combination of electric motors and hydraulics to achieve the necessary pressure. Along with the evolution of presses came the evolution of the dies used within them.

Safety

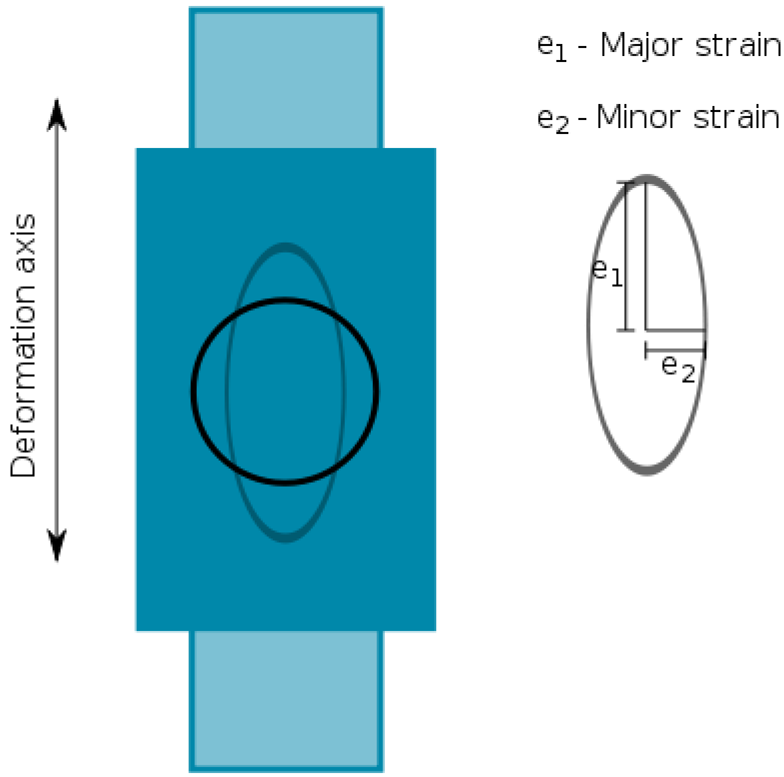
Machine presses can be hazardous, so safety measures must always be taken. Bi-manual controls (controls the use of which requires both hands to be on the buttons to operate) are a very good way to prevent accidents, as are light sensors that keep the machine from working if the operator is in range of the die.

Forming limit diagram

A **forming limit diagram**, also known as a **forming limit curve**, is used in sheet metal forming for predicting forming behaviour of sheet metal. The diagram attempts to provide a graphical description of material failure tests, such as a punched dome test.

In order to determine whether a given region has failed, a mechanical test is performed. The mechanical test is performed by placing a circular mark on the workpiece prior to deformation, and then measuring the post-deformation ellipse that is generated from the action on this circle. By repeating the mechanical test to generate a range of stress states, the formability limit diagram can be generated as a line at which failure is onset

Description



Definition of the deformation axes in forming limit diagram measurement

The semi-axes of the ellipse formed in this circle allow for the measurement of relative strain in two primary directions, known as the major and minor directions, which correspond to the major and minor semi-axes of the ellipse. Under the assumption of path independent strain, the relative strains will reach a critical value at which deformations occurs. Through repeated experimental measurements, the shape of the curve can be obtained experimentally. Alternately, a formability limit diagram can be generated by mapping the shape of a failure criterion into the formability limit domain. However the diagram is obtained, the resultant diagram provides a tool for the determination as to whether a given forming process will result in failure or not. Such information is critical in the design of forming processes, and is therefore fundamental to the design of sheet metal forming processes. Through the establishment of forming limit diagrams for range of alloys, the forming process and alloy behaviour can be matched at the metalworking design time by the process engineer.

Modern determination

With the availability and use of optical strain measurement system in combination with digital data processing forming limit curves can be acquired in a more automatic and productive way compared to the classic way as described above. This procedure has been standardized and is contained in an ISO document (12004).

In order to obtain a full forming limit curve, test pieces with different geometries are drawn by a punch (e. g. with a diameter of 100 mm) until fracture occurs. Friction is almost zero by using a complex tribo-system with foils and grease between sheet and tool. By use of an optical strain measurement system spatial strain paths are evaluated immediately before failure of the test piece. Using an interpolation method for the strain variation between the severely deformed and necked area – the limits of this area are computed by a sign change of the second derivative of the strain distribution – the major and minor strain values are obtained. Using an averaged value for several cross section evaluations and 3 test samples for the same geometry a strain pair (one point in the forming limit diagram) as forming limit is identified.

Influence parameters

Forming limit curves (FLC) for four steel sheet grades are displayed in the attached figure. All forming limit curves have essentially the same shape. A minimum of the curve exists at the intercept with the major strain axis or close thereby, the plane strain forming limit. With the definition of the onset of local necking (e. g. membrane force reaches an extreme value) and the assumption of a hardening law according to Hollomon ($\sigma = K \varepsilon^n$) it can be shown that the corresponding theoretical plane strain forming limit is identical with the strain hardening coefficient, n. There is no thickness effect. Taking into account the strain rate sensitivity of the material, which is obvious in steel, along with the sheet thickness, the fact can be explained that practical forming limits, obtained by the use of the above described method, lie well above theoretical forming limits. Thus the basic influence parameters for the forming limits are, the strain hardening exponent, n, the initial sheet thickness, t_0 and the strain rate hardening coefficient, m. The lankford coefficient, r, which defines the plastic anisotropy of the material, has two effects on the forming limit curve. On the left side there is no influence except that the curve extends to larger values, on the right hand side increasing r values reduce the forming limits.

M-K method

There is a widely used method for computation of FLCs, introduced by Marciniak in 1967. It assumes an inclined band in the investigated plane sheet piece with smaller thickness which denotes an imperfection. With this model limit strains can be calculated numerically. The advantage of this method is that any material model can be used and limits can also be obtained for nonproportional forming. However there is one drawback. Calculated forming limits are sensitive to the imperfection value. With the assumption of a strain rate sensitive material model realistic forming limits may be obtained which lie above theoretical limit strains. Basically with this calculation method smooth forming limit curves are generated for materials for which only one experimental value exists. A good overview of state of the art about FLC calculation methods is given in the proceedings of a conference held in Zurich in 2006 and the Numisheet conference in 2008.

Use of FLCs

For many years forming limit curves have been used in order to assess the sheet material formability. They have been applied in the design stage of tools using the finite element method as a simulation tool which is widely used in a production environment.

Chapter-12

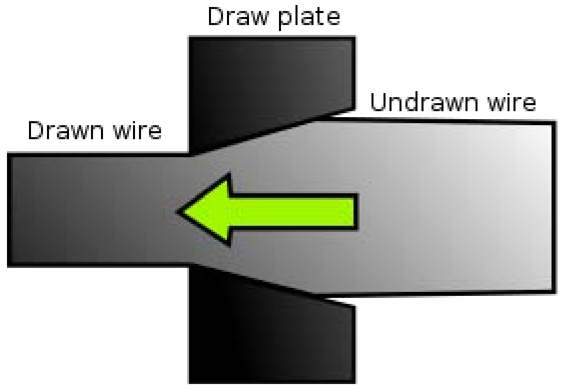
Wire Drawing

Drawing silver wire by hand pulling.

Drawing thicker silver wire by cranked pulling.

Wire drawing is a metalworking process used to reduce the cross-section of a wire by pulling the wire through a single, or series of, drawing die(s). There are many applications for wire drawing, including electrical wiring, cables, tension-loaded structural components, springs, paper clips, spokes for wheels, and stringed musical instruments. Although similar in process, drawing is different from extrusion, because in drawing the wire is pulled, rather than pushed, through the die. Drawing is usually performed at room temperature, thus classified a cold working process, but it may be performed at elevated temperatures for large wires to reduce forces. More recently drawing has been used with molten glass to produce high quality optical fibers.

Process



Wire drawing concept

The wire drawing process is quite simple in concept. The wire is prepared by shrinking the beginning of it, by hammering, filing, rolling or swaging, so that it will fit through the die; the wire is then pulled through the die. As the wire is pulled through the die, its volume remains the same, so as the diameter decreases, the length increases. Usually the wire will require more than one draw, through successively smaller dies, to reach the desired size. The American wire gauge scale is based on this. This can be done on a small scale with a draw plate, or on a large commercial scale using automated machinery. The process of wire drawing improves material properties due to cold working.

The areal reduction of small wires are 15–25% and larger wires are 20–45%. Very fine wires are usually drawn in bundles. In a bundle, the wires are separated by a metal with similar properties, but with lower chemical resistance so that it can be removed after drawing. If the reduction in diameter is greater than 50%, the process may require annealing between the process of drawing the wire through the dies. Commercial wire drawing usually starts with a coil of hot rolled 9 mm (0.35 in) diameter wire. The surface is first treated to remove scales. It is then fed into either a single block or continuous wire drawing machine.

Single block wire drawing machines include means for holding the dies accurately in position and for drawing the wire steadily through the holes. The usual design consists of a cast-iron bench or table having a bracket standing up to hold the die, and a vertical drum which rotates and by coiling the wire around its surface pulls it through the die, the coil of wire being stored upon another drum or "swift" which lies behind the die and reels off the wire as fast as required. The wire drum or "block" is provided with means for rapidly coupling or uncoupling it to its vertical shaft, so that the motion of the wire may be stopped or started instantly. The block is also tapered, so that the coil of wire may be easily slipped off upwards when finished. Before the wire can be attached to the block, a sufficient length of it must be pulled through the die; this is effected by a pair of gripping pincers on the end of a chain which is wound around a revolving drum, so drawing the wire until enough can be coiled two or three times on the block, where the end is secured by a small screw clamp or vice. When the wire is on the block, it is set in motion and the wire is drawn steadily through the die; it is very important that the block rotates evenly and that it runs true and pulls the wire at a constant velocity, otherwise "snatching" occurs which will weaken or even break the wire. The speeds at which wire is drawn vary greatly, according to the material and the amount of reduction.

Continuous wire drawing machines differ from the single block machines in having a series of dies through which the wire passes in a continuous manner. The difficulty of feeding between each die is solved by introducing a block between each die. The speeds of the blocks are increased successively, so that the elongation is taken up and any slip compensated for. One of these machines may contain 3 to 12 dies. The operation of threading the wire through all the dies and around the blocks is termed "stringing-up". The arrangements for lubrication include a pump which floods the dies, and in many cases also the bottom portions of the blocks run in lubricant.

Often intermediate anneals are required to counter the effects of cold working, and to allow more further drawing. A final anneal may also be used on the finished product to maximize ductility and electrical conductivity.

An example of product produced in a continuous wire drawing machine is telephone wire. It is drawn 20 to 30 times from hot rolled rod stock.

While round cross-sections dominate most drawing processes, non-circular cross-sections are drawn. They are usually drawn when the cross-section is small and quantities are too low to justify rolling. In these processes, a block or Turk's-head machine are used.

Lubrication

Lubrication in the drawing process is essential for maintaining good surface finish and long die life. The following are different methods of lubrication:

- Wet drawing: the dies and wire or rod are completely immersed in lubricant
- Dry drawing: the wire or rod passes through a container of lubricant which coats the surface of the wire or rod
- Metal coating: the wire or rod is coated with a soft metal which acts as a solid lubricant
- Ultrasonic vibration: the dies and mandrels are vibrated, which helps to reduce forces and allow larger reductions per pass

Various lubricants, such as oil, are employed. Another lubrication method is to immerse the wire in a copper (II) sulfate solution, such that a film of copper is deposited which forms a kind of lubricant. In some classes of wire the copper is left after the final drawing to serve as a preventive of rust or to allow easy soldering.

Mechanical Properties

The strength-enhancing effect of wire drawing can be substantial. The highest tensile strengths available on any steel have been recorded on small-diameter cold-drawn austenitic stainless wire. Tensile strength can be as high as 400 ksi (3760 MPa).

Drawing dies

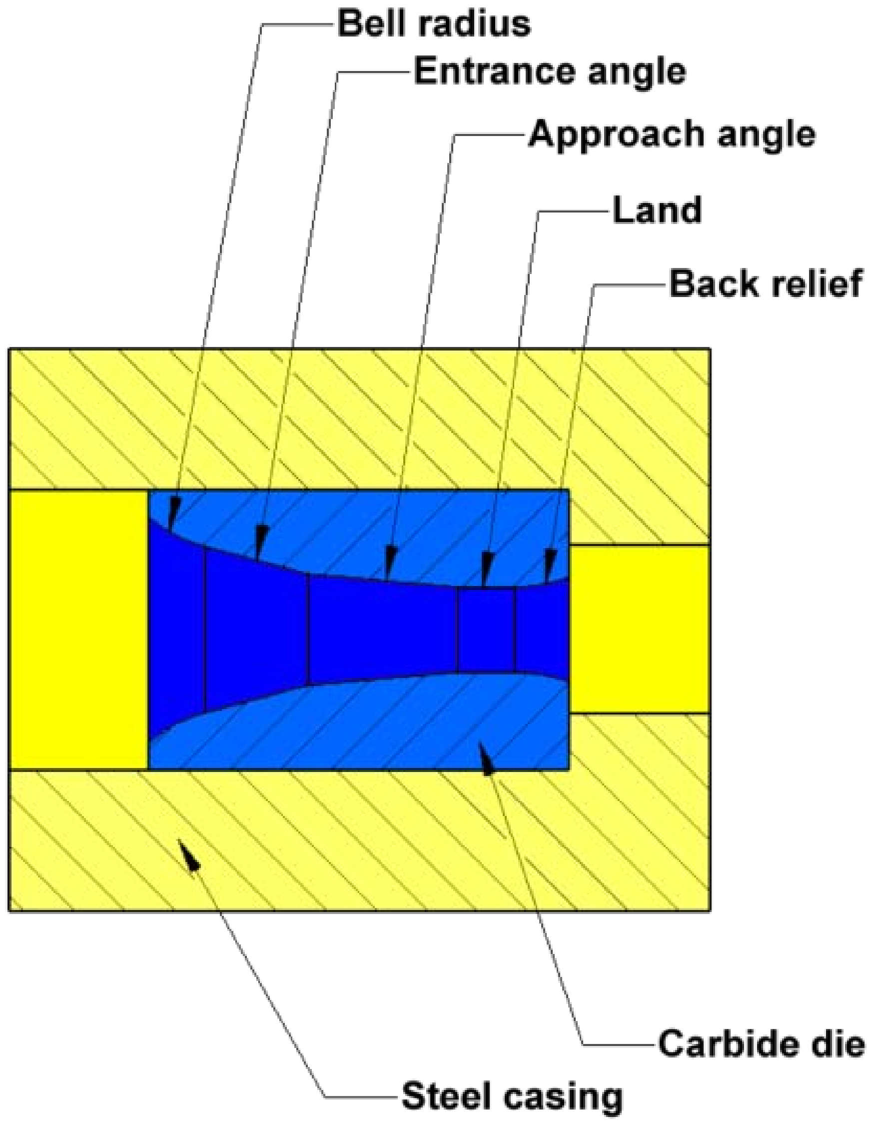


Diagram of a carbide wire drawing die

Drawing dies are typically made of tool steel, tungsten carbide, or diamond, with tungsten carbide and manufactured diamond being the most common. Synthetic diamond is usually used in the early stages of the drawing process, whereas natural diamond dies are used in the final stages. For drawing very fine wire a single crystal diamond die is used. For hot drawing, cast-steel dies are used. For steel wire drawing, a tungsten carbide die is used. The dies are placed in a steel casing, which backs the die and allow for easy die changes. Die angles usually range from 6–15°, and each die has at least 2 different angles: the entering angle and approach angle. Wire dies usually are used with power as to pull the wire through them. There are coils of wire on either end of the die which pull and roll up the wire with a reduced diameter.