Introduction to Manufacturing Methods for Metals

Part 1

Casting and Forging Methods

by

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Introduction to Manufacturing Methods for Metals

A SunCam online continuing education course

Contents

1.0   Course Overview

A basic understanding of manufacturing processes is very important for many engineering fields. Economical product design requires the understanding of manufacturing processes to determine how the product will be made. The choice of manufacturing method will depend on things such as part size and shape and the quantity to manufacture. There are numerous manufacturing methods, so it can be difficult to determine the optimal method for a particular part. The engineer needs to be familiar with the available methods and understand the advantages and disadvantages of each method.

The course is not intended to make the reader an expert in any particular manufacturing method. Full understanding of metal manufacturing methods would require a detailed coverage of topics such as thermodynamics, heat transfer, chemistry, and material science. This course provides a general overview of two common categories of manufacturing methods for metals: casting and forging. The main focus is more on developing the understanding on how to design parts to be manufactured using the different processes and how to select the proper process for a particular part.

It can be difficult to fully understand any manufacturing process by simply reading about the process. Figures are provided to add clarity when possible, but figures are not the best visual aid for explaining manufacturing methods. Links to videos are also provided where applicable. The reader is encouraged to watch these short videos to gain a better understanding of the processes.

2.0   Metal Casting

2.1   Introduction

Metal casting is a process of allowing a molten metal to solidify in a mold cavity. The molten metal can either flow into the mold by gravity or it can be injected into the mold by force. Metal casting allows for the creation of complex part geometries with external and internal features. Very large parts can be casted, especially with sand casting. Metal casting can also be well suited for mass production of parts.

2.1.1   Classification of Metal Casting Methods

Metal casting processes can be classified by the mold type or the pressure used to fill the mold. Sand casting, for example, typically utilizes a permanent pattern but has molds that can only be used once (expendable molds). Expendable mold casting is a process where the mold is sacrificed in order to remove the cast part. Expendable mold processes will have a limited production rate due to the time required to make new molds. Permanent molds made of metal can also be used, and the molds are reusable. Permanent mold casting and die casting are examples of processes where the mold is not destroyed to remove the part (not expendable molds). Permanent mold casting processes have much higher production rates. Investment casting is another casting methods that has expendable molds and expendable patterns.

There are advantages and disadvantages to each general process. The sections to follow will highlight the different advantages and disadvantages and provide additional details for each method.

2.1.2   Metals used for Casting

Metals used for casting are generally alloys and classed as ferrous (contain iron) or nonferrous (contain no iron). It will be discussed in the following sections, but some casting methods may be limited to one of the two classifications. Sand casting and investment casting can be used for all metals. Die casting is commonly used for zinc, magnesium, brass and aluminum. Permanent mold casting is limited to nonferrous materials.

2.2   Sand Casting

2.2.1   Introduction

Sand casting uses a mold of specially prepared sand. The sand mold is broken to remove the casting, so it is an expendable mold process. Figure 1 shows an example of sand castings being poured.

Of the casting methods, sand casting is the most commonly used and offers many advantages. Sand castings can be made in almost any size, so it is a very common process for large castings. The process allows for a very wide variety of shapes, some of which would be impossible to

make using other casting methods. Though production rates are overall lower for sand casting compared to permanent casting methods, sand casting production can often be partially or fully automated. Sand casting is very versatile and can be used for casting both ferrous and nonferrous metals.

Figure 1   Pouring sand castings at the Ford foundry

Sand casting also has some disadvantages. There is added cost from patterns and cores (more details on both of those are provided next). The outer layer (skin) of a sand cast part may contain sand, which can cause rapid wear in cutting tools and machining tools. Allowances need to be made for size variations, and these allowances are high in sand casting compared to other casting methods.

It is very important for a design engineer to understand the process of sand casting, because it is possible to design a part for sand casting that cannot be fabricated using sand casting. For example, some parts may not be suited for sand casting based on the required shape of the part.

2.2.2   Pattern

A pattern is an approximate full-sized duplicate of the final casting and is used to form the mold cavity. Patterns can be made from different materials such as wood, plastic, brass, or aluminum. Patterns can be re-used, and metal patterns should be used if a lot of castings will be made from the same pattern.

A pattern is manufactured based on an engineering drawing. The pattern, which is usually made in two parts, will not be the same size as the final desired part. For example, it must allow for shrinkage of the part. Extra material must be available for surfaces that must be machined after casting, so the pattern must be oversized to account for machining processes. Draft angles must be considered to allow the pattern to be removed from the sand mold.

2.2.3   Cores

For hollow castings a core is an object placed into a mold to produce an internal opening in the casting. The core will occupy the space in the mold for the hollow section, and metal will flow around a core within a mold. Cores are made from sand with a binder, and must be strong enough to withstand the forces during the final casting process. Cores must be supported in the mold cavity, so patterns are made in a way to provide core supports in the mold. When the casting is complete the core will break down during the removal of the cast part.

2.2.4   Mold

2.2.4.1   Molding Sand

Sand casting uses a molding sand that is composed of clean silica sand, clay, water and additives. Water content is generally between 3 and 4 percent by weight. If the water percentage is too low the mold will be weak. The clay (commonly bentonite) is added as a binder because natural sand does not stick effectively. Cereal flours (such as corn or wheat) are used as an additive. The cereal flour will burn in the heat to leave voids to allow the sand to expand.

Sand molds are classified as green sand molds and dry sand molds. Regardless of what the name suggests, green sand molds are not named because of color; Green sand molds are molds containing moisture at the time of pouring. Dry sand molds are baked to reduce moisture. The

baking will strengthen the mold and it will harden the mold cavity. Dry sand molds have the advantage of improved dimensional control, but there is the extra cost of baking. Baking also adds time which affects production time. Molds can also be skin dried, where the surface of the mold that is in contact with the molten metal is dried. Synthetic resin can also be mixed with the sand to provide a mixture that will harden at room temperature.

2.2.4.2   Features of the Mold and Mold Construction

Sand casting molds consist of several parts, and they are constructed in a particular order to construct the mold. The features are explained in the first half of this video, which can be viewed in conjunction with reading this section to get a full understanding of the features. Note that the second half of the video discusses investment casting, which will be discussed in Section 2.3.

The bottom molding board provides a smooth surface during construction of the mold. The side walls of the mold are called the flask, and they support the mold. The flask is divided into two halves. The bottom half of the flask is called the drag and the upper half of the flask is called the cope. The drag is placed on the molding board, then the half pattern is placed in the proper location. Sand is added to the drag and compacted around the pattern. A board is clamped to the top of the drag, and the drag is turned over. The cope is then added to the drag and aligned with pins. The upper half of the pattern is placed in the proper location and located with pins.

Once the cope and upper pattern are in position, some other components must be added. Pegs are positioned that will form the sprue and risers. The sprue will serve as the location where the molten metal will be poured into the mold. Risers are essentially reservoirs that will supply additional molten metal while the casting shrinks as it cools. Once the pegs are positioned for the sprue and risers, the cope is filled with sand. The pegs are then removed to leave the sprue and risers. A pouring basin is formed in the sand and serves as a funnel to the sprue.

The cope is then removed from the drag to allow for the removal of the pattern. The runner system, which carries the molten metal from the sprue to the mold cavity, is cut into the drag. The cope is then placed back on the drag to form the final mold.

Gates are the connecting point between the runner system and the actual mold cavity. It is common for larger parts to have multiple to gates to provide multiple feeding points for material to enter the mold cavity.

2.2.4.3 General Mold Design Considerations

Though the full details of mold design are not the main focus of this course, it is important to understand some of the main considerations for designing molds. It is important to have a sprue design that allows for the proper flow rate while avoiding turbulence. Runners are generally rectangular in cross-section, and abrupt changes in direction should be avoided in runner systems. Gates should be located so that material feeds into the thicker sections of the casting. Another consideration for gates is to design them in a way to reduce turbulence in the flow of material into the casting. Rectangular cross-sections are the most common for gates with fillets between the gate and casting to reduce turbulence. It is also desirable to have a slight flare of the gates toward the casting.

The mold must fill quickly compared to the overall solidification time, while again avoiding turbulence. The mold should be designed so that solidification begins at one end and progresses through the casting with the risers solidifying last. Riser design is critical to ensure that they have a large enough volume to compensate for shrinkage. Riser location is based on areas within the mold that will require more material during shrinkage. A critical criterion for risers is that risers must solidify last. Therefore, risers should have a greater volume to area ratio than the actual part so the part solidifies before the riser. Risers typically are cylindrical in shape because of the high volume to area ratio.

Computer programs can greatly aid in the design of molds. Fluid flow into the mold can be modeled using Bernoulli's equation and continuity equations. The software can provide velocity and pressure information in the runner system. Heat transfer in the casting can also be modeled.

2.2.5   Making the Casting

Once the mold is constructed, the cast part is ready to fabricate. Molten metal is tapped from a furnace and transferred to the mold. The molten metal is poured through the sprue until the mold cavity is full. Once the casting has fully solidified, the sand mold is shaken apart on a vibrating conveyor. The vibration also removes the core. All of the sand will drop into a pit to be reconditioned.

As shown in Figure 2, the casting will still have the solidified sprue, risers, and runners. All of these components are trimmed off to leave the final cast part. Finishing processes, such as machining, can now be completed.

Figure 2   Bronze cast part before trimming sprue and risers

2.3 Investment Casting

Investment casting (also called lost wax casting) is a slow and expensive process, but it may be a profitable option for pilot runs for small quantities. Investment casting uses expendable molds and expendable patterns. The patterns are made of wax or polystyrene, and a pattern is made for every single part cast using molds. The patterns are then attached to a common sprue using heat or adhesive. The patterns and sprue form a tree (or cluster) of parts. The process of making the tree of parts is called clustering, and it is done by hand. The process of investment casting is explained in the second half of this video. The last portion of the video discusses evaporative foam casting, which is a method similar to investment casting that uses foam in lieu of wax.

The next process is called investing, where the pattern tree is covered with a heat-resistant material such as fine silica. The first layers of material are fine to get a smooth surface. Outer layers are a coarser ceramic material.

The mold is then heated to burn out the wax or plastic pattern material. This process, which is called burning out or dewaxing, will leave voids containing the part imprints and runner system.

The molten metal can now be poured into the mold by gravity. After solidification occurs, the mold is broken away. The individual parts are then cut off the sprue and runner system and cleaned.

Investment casting is typically used for small castings, weighing 5 pounds or less. However, the process can be used for medium sized parts.

You can also watch this video for more examples of investment casting processes.

2.4 Permanent Mold Casting

We will now discuss permanent mold casting, which is a method to produce many castings from each mold. Unlike expendable mold methods, the mold is not destroyed to remove the cast part. Therefore, the mold must be designed in a way that the part can easily be removed. Part shapes cannot be overly complex (unlike sand casted parts) because complex parts cannot be removed from a rigid permanent mold. The molds are commonly made from steel, and the molds contain the entire shape of the final part along with sprue and runner system. Steel cores can be used if they be retracted out of the part before the mold opens. Mechanisms need to be used to retract the cores. Multiple parts can be made with a single mold if the parts are small.

Casting made with permanent molds will solidify faster due to better heat transfer. The faster solidification provides castings with finer grain structure and better strength. The castings will have better tolerances and surface finish compared to sand casting. Production is confined mostly to nonferrous alloy castings.

An example process of permanent mold casting can be seen in this video.

2.5 Die Casting

2.5.1 Introduction

Die casting is a fast and efficient process for production of small to medium sized metal parts. In die casting, the molten metal is injected into the mold cavity at high pressure. That pressure is then maintained during solidification of the part. Once the part has solidified, the mold is opened and the part is removed. The die casting process is faster than permanent mold casting, but the

equipment is far more expensive. Therefore, die casting is only feasible for production in large quantities. Figure 3 shows an example of a die casting machine.

Figure 3   Die casting machine

The dies are made from tool steel, and the die contains all the features of the part along with the complete runner system. Dies can be single cavity (one part made at a time) or multiple cavity (multiple parts per die). The dimensions of the impression of the part in the die will allow for shrinkage of the part when cooling. Cores can be part of the die or have mechanisms to withdraw them from the die cavity before removal of the part. The die block often contains cooling coils to circulate water and solidify the part more rapidly.

Die castings have dimensional tolerances of 0.005 – 0.01 inches. Therefore, many die cast parts are completely finished when removed from the die and often require no finishing processes such as machining. If machining is required, the machining allowance is generally between 0.01 – 0.03 inches. Die casting also allows for casting of thin sections.

Die casting is primarily limited to nonferrous alloys. This limitation is due to the higher temperatures required for ferrous metals. The higher temperatures cause rapid deterioration of the dies.

2.5.2   Cold Chamber vs. Hot Chamber

There are two general methods of die casting: cold chamber and hot chamber. The difference between the methods is based on the method of forcing the metal into the die. Details of the two methods is beyond the scope of this course and not critical for a design engineer designing parts for fabrication, so only a general overview of the methods will be provided.

In the cold chamber process, the molten metal is kept in a separate heated holding crucible. The molten material is poured into a chamber and a plunger drives the material into the mold. Cold chamber processes are used for aluminum and brass alloys.

The hot chamber process is more automatic. The molten metal is in a melting pot, and a plunger automatically presses material from the melting pot into the mold. Hot chamber processes are used for zinc and zinc alloys.

The different die casting machines are best understood by watching examples, which can be seen in this video.

2.6   Selecting the Best Casting Process

Several casting methods have been discussed. Part of the role of the engineer is to select the most feasible casting method for a particular part. Selecting the best casting process depends on the type of metal used, the required number of parts to manufacture, the overall shape and size of the part, and the required dimensional accuracy and surface quality of the part. It is also important to consider any finishing processes required, such as machining.

2.7 Design Considerations for Casting

2.7.1 Solidification of Metals

When designing a part that you plan on manufacturing through casting processes, it is important to have a general understanding about how metals solidify in a mold. Solidification is the process where the molten metal cools and returns to a solid state. Solidification will be different for pure metals and alloys. Pure metals solidify at a constant temperature known as the melting point, and these melting points are well known for pure metals. Most alloys, however, solidify over a temperature range. The exact range will depend on the actual composition of the alloy.

When molten metal is placed in a mold, heat will dissipate from the surface through the mold. Therefore, solidification will begin on the outer surface of the part and progress inward in layers. Because the mold walls are typically room temperature, a quick chilling action at the mold wall will cause a thin skin of solid metal to initially form in the casting. As cooling continues, further grain formation occurs in directions away from heat transfer as shown in Figure 4.
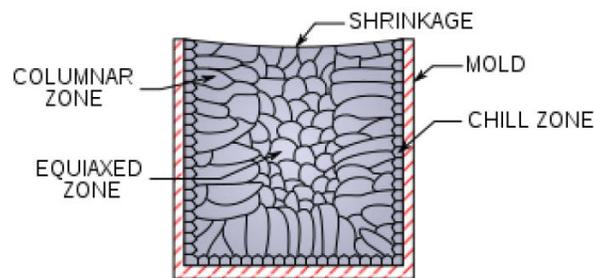

Figure 4   Solidification in a casting

As the molten metal solidifies it will contract in volume. Risers are added to a casting system to account for the shrinkage during cooling. Risers are essentially reservoirs to supply additional molten metal to the casting during the solidification process. The locations or risers in the casting system are important. Risers should be placed so the casting solidifies toward the riser so that the risers solidify last. Risers are typically cylindrical in shape to slow cooling time of the actual riser material. The size of the risers must be considered because if risers are too small

they will not be able to provide enough material during cooling. If a riser is too large it will add overall time to the solidification process.

2.7.2   General Design Rules

2.7.2.1   Part Defects

Cast parts can have defects, with porosity being a very common example. Defects most commonly occur due to non-uniform cooling during solidification, especially for parts with more complex geometry. Therefore, if casting is to be used for part fabrication, it is important to design the part geometry to try to ensure uniform cooling. The general design guidelines to follow will aid in uniform cooling and reduce part defects.
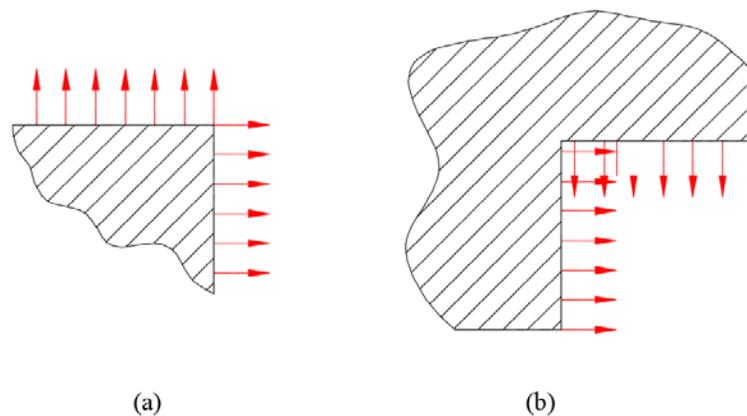

Figure 5   Non-uniform cooling (a) an outside corner (b) an inside corner

2.7.2.2   Sharp Corners

One general guideline for designing cast parts is to avoid sharp corners. The first problem with sharp corners is that they cause non-uniform solidification rates. Outside corners will cool faster while inside corners will create a hot spot and cool slower. Both scenarios are illustrated in

Figure 5. The arrows illustrate the dissipating heat. Cooling will be more uniform for both cases by rounding the corner.

2.7.2.3 Uniform Thickness

Another general design guideline is to keep sections as uniform in thickness as possible. Consider the corner shown in Figure 6 (a). The inside corner has a fillet, which satisfies the previous guideline of rounded corners. The outside edge is square, which causes a non-uniform thickness at the corner. Cooling will not be uniform at the corner and could cause a void to form in the corner as shown. An improved design is shown in Figure 6 (b) where the thickness is uniform around the corner.
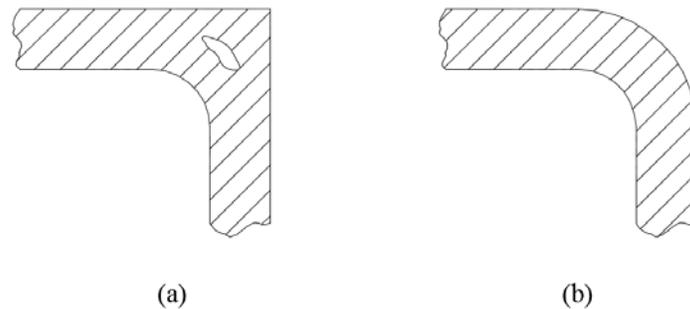

(a)   (b)

Figure 6   (a) Corner with non-uniform thickness (b) Corner with uniform
                  thickness

Another guideline, that is basically an extension of the previous guideline, is to avoid abrupt changes in thickness or cross-section. Figure 7 (a) shows an abrupt thickness change, which should be avoided due to non-uniform cooling. Improvements can be made by rounding the corners, as shown in Figure 7 (b), or by tapering the change, as shown in Figure 7 (c). It should be noted that sharp corners and abrupt changes are not only poor design for casted parts. Abrupt changes will also cause stress concentrations.
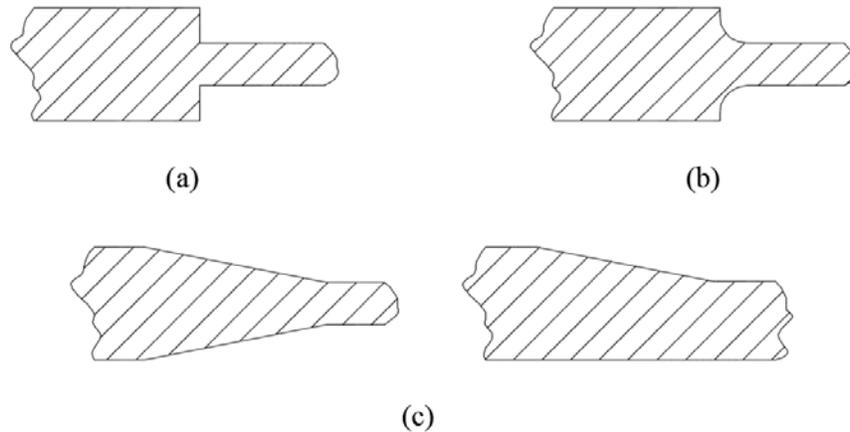
Figure 7 (a) Abrupt thickness change (b) Thickness change with rounded corners (c) Tapered thickness change

Large flat surfaces on a part should be avoided. One issue will be warpage during cooling, but another issue can be poor surface finish due to uneven flow during the filling of the mold cavity. It can help to break up flat surfaces with staggered ribs to increase the stiffness and reduce warping.

2.7.2.4   Shrinkage
Issues with shrinkage during cooling have already been discussed. The pattern is made with shrinkage allowance, which is known as patternmaker's shrinkage allowance. The shrinkage allowance is typically between 1/8 in/ft to 1/4 in/ft (10mm/m to 20mm/m).

2.7.2.5   Draft
Small draft angles should be included on sand mold patterns to aid in the removal of the pattern without damaging the sand mold. The draft angles typically fall between 0.5° to 2°.

2.7.2.6   Parting Line and Part Orientation

The overall orientation of a part in a mold should be done in a way to minimize overall height. It should also be oriented so that the largest part of the casting is relatively low.

The pattern will have an upper and lower portion. Therefore, a parting line will exist at the plane separating the cope and drag (upper and lower halves of the mold). The ideal location of the parting line on the part will depend on several factors. Ideally the parting line will be located in a region that is flat. It is common for the surface with the parting line to require machining, and you want to try to eliminate machining on draft surfaces. The parting line should be placed at the cross-sectional location of the largest area of the casting.

For materials with lower density, such as aluminum, you want to place the parting line lower on the casting. For higher density materials you want to place the parting line around mid-height.

2.7.2.7   Tolerances and Machining Allowance

Casting cost will increase for tighter dimensional tolerances. Therefore, it is important to keep dimensional tolerance requirements as wide as possible. Patterns should be constructed with machining allowances for any areas that will require machining or other finishing operations.

2.7.2.8   Engineering Drawings

Detail drawings for parts made using casting processes need to include information about material, casting tolerance, and machining allowance. Casting drawings will contain all the necessary information for the foundry operations involved in making the casting. The drawing will include extra material for machining allowance. Details for the final machined part can be on a combined drawing that contains information about the casting and the final part or on a separate machining drawing. Combined drawings are sometimes confusing and can cause production delays. With the current technology of drafting software, it is very easy to provide separate drawings for the cast part and the machined part. The goal is make the drawings simple and clear to reduce confusion.

It is also common to incorporate part identification markings into a cast part. Lettering can be added in a mold to provide part numbers.

3.0 Metal Forging

3.1 Introduction

To get a very basic idea of forging you can picture a blacksmith hammering out shapes from hot steel. That process is a basic example of simple open die forging. Forging is a process of shaping metal using hammers or presses and commonly uses dies. Forging is generally used to get the part close to the desired size and shape. Finishing methods, such as machining, can then be done to get the part to the final dimensions.

Forging has some advantages over other manufacturing methods for metals. In forging, the grain flow follows the overall shape of the part. Therefore, the part is stronger, tougher, and more ductile. Forging processes can be automated and production rates are good. Practically all metals can be forged.

Some disadvantages include the high cost for forging presses and dies. Additional equipment, such as heating furnaces and trimming equipment, may also be required increasing cost.

3.2 Forging Classification

There are different ways to classify forging processes. One classification is based on the working temperature of the part and separates hot forging and cold forging. Hot forging is used when significant deformation is needed, so the part is heated to increase ductility of the work metal. In hot forging, a blank (or slug) of the material is cut to size and heated in a furnace prior to the forging process. Cold forging has the advantage of increased strength resulting from strain hardening. For hot forging, it is important to obtain the correct temperature for the workpiece. If the temperature is too low, the forging process will require more pressure. If the temperature is too hot, melting may occur within the forging. Isothermal forging is a specialized hot forging operation in which the die surfaces are heated to reduce heat transfer from the workpiece into the tooling. In isothermal forging, the workpiece is maintained at a temperature near its starting temperature to avoid chilling of the workpiece at its contact with the die surface.

Another classification method is based on how the force is applied to the work metal. Methods can include impact methods, such as a forging hammer, or gradual pressure from a forging press. The main types of forging machines are drop hammers and forging presses. Drop hammers have

a heavy falling weight (hammer) and are used for flat die forging. Forging presses can be driven mechanically (crank or skotch-yoke drive) or hydraulically. Forging presses are more expensive than hammer types, but they often use fewer forging strokes to fabricate a part.

The last classification is based on how the work material is constrained during forging. The three categories are open die forging, impression die forging, and closed die forging (also called flashless forging).

To get an introduction to the basic idea of forging and the different forging methods, watch this video. One other forging type is known as roll forging, and is a process that can be used in certain applications. The rolls have the shape of the part machined into a portion of their diameter. The process can be seen in this video.

Figure 8   Open die forging

3.3 Open Die Forging

Open die forging is a method of compressing the work material between two flat (or nearly flat) dies. Figure 8 shows the basic process of open die forging.

Consider a forging process for a simple workpiece that is cylindrical in shape, as illustrated in Figure 9. The cylindrical workpiece has an initial height of h_i and an initial diameter of d_i. Compressing the workpiece between two flat dies will reduce the cylinder's height and increase its diameter as shown in Figure 9 (a). The increase in diameter is known as upsetting. If the contact surface between the flat dies and the workpiece is frictionless, the increase in diameter will be constant. The forging process will result in a new cylindrical shape with a final diameter of d_f and a final height of h_f. For this process $d_f > d_i$ and $h_f < h_i$.
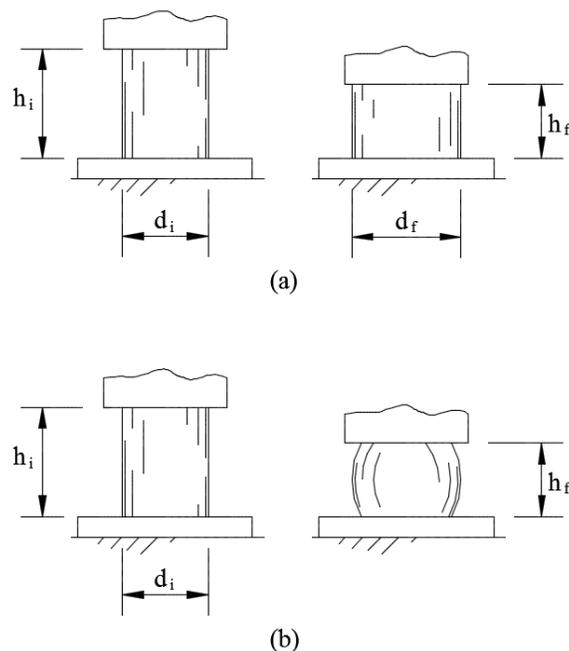

Figure 9 Deformation in open die forging (a) Homogeneous deformation (b) Barreling

If friction exists, the increase in diameter will be less at the surface and more in the central region. This non-homogeneous deformation is known as barreling and is illustrated in Figure 9 (b).

One advantage of open die forging is the ability to forge very large workpieces. Long workpieces can be incrementally forged in a process known as cogging. In cogging, the deformation is local rather than deforming the entire part at once. Open die forging also has the advantage of simple tooling.

Examples of open die forging can be seen in this video.

3.4   Impression Die Forging

Impression die forging is a forging process using die surfaces that contain a shape or impression that contains the inverse of the desired part shape. Impression die forging is often completed in more than one stage, where each stage develops the part toward the final shape. The dies experience high forces at elevated temperatures, which causes rapid wear and decreases dimensional consistency of the parts.

Examples of impression die forging can be seen in this video.

3.4.1   Flash

Figure 10 (a) illustrates impression die forging. In impression die forging, metal material will flow beyond the die cavity as the die closes. The extra material will flow into small gaps between die plates to form flash. Flash is trimmed off the part in a trimming operation, as shown in Figure 10 (b).

Flash also serves an important role during the forging process. As flash forms in the gaps in the die, the flash cools quickly and prevents additional material from leaving the die.
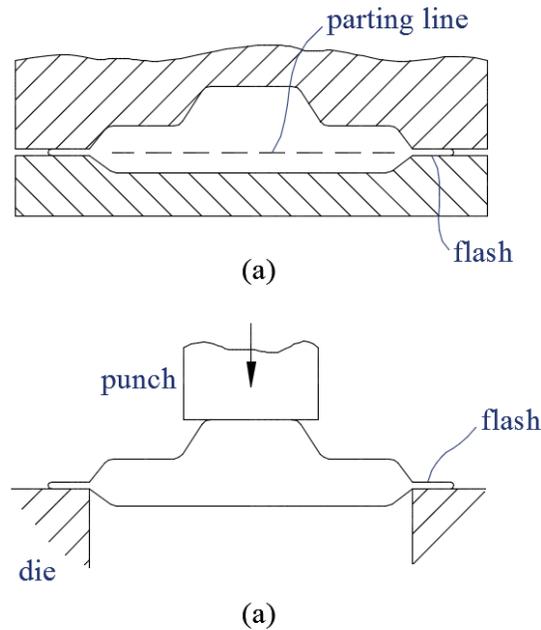
Figure 10   (a) Impression die forging (b) Trimming

3.5 Flashless Forging (Closed Die)

In closed die forging the work material is completely constrained within the die and no flash is formed. The dies are more complex compared to impression die forging. Closed die forging will generate a part with a good surface finish, which commonly results in little to no finishing work on the part. Figure 11 shows an example of a closed die forging process.

Figure 11   Alcoa Forging Division 50,000-ton closed die forging press

Closed die forging has higher requirements for process control. The initial volume of the billet must equal the volume of the die cavity within tight tolerances. If the billet is too small, then the die cavity will not be completely filled. If the billet is too large, excessive pressure will develop and damage the die cavity.

3.6 Ring Rolling

Ring rolling is a variation of forging used to produce seamless ring shapes. Ring rolling mills are used to radially compress the ring shape to change the diameter. An example of ring rolling can be seen in this video.

3.7 Design Considerations for Forging

Engineering drawings for forged parts need to include information about forging tolerances, draft angles, machining allowances, and information about required heat treatment.

3.7.1 Draft Angle

Draft is a slope that exists on side walls of the die. The draft aids in removal of the forging from the die. Typical draft angles are 7° for exterior edges and 10° for interior edges, as shown in Figure 12. The exterior surface can often have a smaller draft angle because the outside surface will shrink away from the die and allow for easier removal. If smaller draft angles are required, the production difficulty will increase and ejection mechanism are required to remove the part.
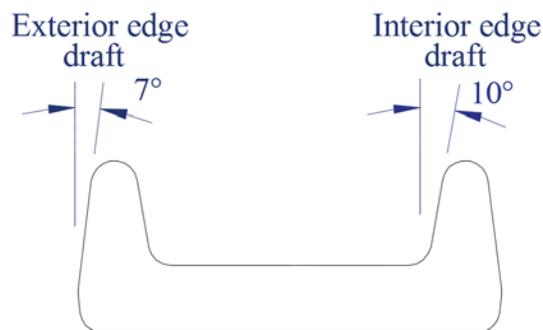

Figure 12   Draft angles and corner / fillet radii

3.7.2   Corner and Fillet Radii

Metal flowing in a die will not be able to change flow direction abruptly. Therefore, corner and fillet radii (both are illustrated in Figure 12) should be sufficiently sized to allow for proper flow of the material. Sharp fillets can cause the formation of cold shuts, which is a lapping of surfaces in a forging that fold against each other. The cold shut will result in a weak spot in the forging.

3.7.3   Parting Line

As with castings, it is important to determine the desired location of the parting line (sometimes called the flash line in forging). The parting line is the line formed at the separation plane of the two dies, which was illustrated in Figure 10. The location of the parting line must be established to determine the location and angle of draft required.

3.7.4   Finish Allowance

Extra material must be added to the overall forged shape if machining or finishing operations are to be performed. The amount of machining allowance depends largely on the oxidation behavior of the material. Material such as aluminum and magnesium alloys are sometimes forged with zero machining allowance because the materials do not oxidize significantly at the temperatures used in forging. Most other metals will oxidize at forging temperatures and will require some type of finishing process after forging.

3.7.5   Forgeabilty

Forgeability is a measure of a metal's ability to be forged. It is important to note that not all metals have equal forgeability. In general, forgeability increases with temperature. However, there is a maximum limit on how high the temperature can go without having undesirable conditions such as melting of a phase. Fine grain metals have a higher forgeability.

Alloys such as aluminum, magnesium, and copper have the best forgeability. Carbon steel also has a high forgeability. Nickel alloys and titanium alloys have average forgeability. Tungsten and beryllium have the lowest forgeability.

4.0   Conclusions and Summary

This course focused on two primary categories for metal fabrication: casting and forging. As an engineer, you should design part based on the desired fabrication method. Though this course did not cover every aspect of these fabrication methods, it should have provided background information to allow for a better understanding of how these methods can be used for product manufacturing.