UNIT 2 METAL FORMING

2.1. INTRODUCTION

Metal forming can be defined as a process in which the desired size and shape are obtained through the deformation of metals plastically under the action of externally applied forces. Metal forming processes like rolling, forging, drawing etc. are gaining ground lately. It is due to the fact that metal forming is the wasteless process which is highly economical. They give high dimensional accuracy, easy formability for complex shapes and good surface finish with desired metallurgical properties.

The metal forming is based upon the plastic deformation of metals. For finding out the complete information of the stresses and strains that developed in the metal due to application of loads, comprehensive study and calculations are required.

To start with, there are three conditions to be satisfied, while going for stress estimation:

- There should be equilibrium at all points.
- The volume should remain same before and after the forming.
- Stress-strain relationship of material should be maintained.

There are two methods for analysing forming processes:

1. Lower bound method
2. Upper bound method

The main objective is to find out the yield stress developed in the material body and its distribution in the material. This helps in estimating the load required for the initiation of the process and its maximum value that a body can bear. If the body is under single load e.g., only tensile load or only compressive load is applied to a body, then the yield stress can be measured easily by stress-strain diagram, but in reality different loads are there on body which make the process complex and thus also make it difficult to find out the yield stress distribution in the body.

2.2 ELASTIC AND PLASTIC DEFORMATIONS

Deformation is the change in dimensions or form under the action of applied load. Deformation is caused either by mechanical action of external load or by various physical and physicochemical processes. The process of deformation comprises the following consecutive stages

(a) Elastic deformation

(b) Plastic deformation

(c) Fracture

Elastic deformation of a material is its power of coming back to its original position after deformation when the stress or load is removed i.e., deformation completely disappears after removal of load.

The **plastic deformation** means that the material undergoes some degree of permanent deformation without failure on application of load. Plastic deformation will take place only after the elastic range has been exceeded. Plastic deformation is important in case of forming, shaping, extruding and many other hot and cold working processes.

Due to this various metal can be transformed into different products of required shape and size. This conversion into desired shape and size is affected either by the application of pressure, heat or both.

The plastic deformation of metals may occur in the following ways

(1) By slip

(2) By formation of twins

(3) Deviations from regular positions of atoms

(4) Breakdown of structure.

2.3 HOT WORKING AND COLD WORKING

2.3.1 Hot Working

(a) Properties

1. Hot working is done at a temperature above recrystallization but below its melting point. It can therefore be regarded as a simultaneous process of deformation and recovery.
2. Hardening due to plastic deformation is completely eliminated by recovery and recrystallization.
3. Improvement of mechanical properties such as elongation, reduction of area and impact values.
4. Difficult to handle a hot worked metal.
5. Poor surface finish due to oxidation and scaling.
6. Refinement of crystals occurs.

7. Due to hot working cracks and blowholes are welded up.

8. No internal or residual stress developed.

9. Force required for deformation is less.

10. Light equipment is used in hot working.

11. Hot working processes are—hot forging, hot rolling, hot spinning, hot extrusion, hot drawing, and hot piercing.

(b) Advantages of Hot Working

1. Porosity in the metal is largely eliminated. Most ingots contain many small blow holes. These are pressed together and eliminated.

2. Impurities in the form of inclusions are broken up and distributed throughout the metal.

3. Coarse or columnar grains are refined. Since this hot work is in the recrystalline temperature range, it should be continued until the low limit is reached to provide a tine grain structure.

4. Physical properties are generally improved owing principally to grain refinement. Ductility and resistance to impact are improved, strength is increased, and greater homogeneity is developed in the metal. The greatest strength of rolled steel exists in the direction of metal flow.

5. The amount of energy necessary to change the shape of steel in the plastic state is far less than that required when the steel is cold.

(c) Disadvantages/Limitations of Hot Working

1. Because of the high temperature of the metal, there is rapid oxidation or scaling of the surface with accompanying poor surface finish.

2. Difficult to achieve close tolerances due to scaling.

3. Some metals cannot be hot worked because of their brittleness at high temperatures.

4. Hot working equipment and maintenance costs are high.

2.3.2 Cold Working

(a) Properties

l. Cold working is done at temperature below recrystallization temperature. So, no appreciable recovery can take place during deformation.

2. Hardening is not eliminated since working is done below recrystallization temperature.

3. Decreases elongation, reduction of area etc.

4. Increase in ultimate tensile strength, yield point and hardness.

5. Good surface finish is obtained.
6. Crystallization does not occur. Grains are only elongated.
7. Possibility of crack formation and propagation is great.
8. Internal and residual stresses are developed in the metal.
9. Force required for deformation is high.
10. Heavy and powerful equipment is used for cold working.
11. Easier to handle cold parts.
12. Cold working processes are—cold rolling, cold extrusion, press work (drawing, squeezing, bending, and shearing).

(b) Advantages of Cold Working

1. Cold working increases the strength and hardness of the material due to the strain hardening which would be beneficial in some situations. Further, there is no possibility of decarburisation of the surface.

2. Since the working is done in cold state, hence no oxide formation on the surface and consequently,
good surface finish is obtained.
3. Greater dimensional accuracy is achieved.
4. Easier to handle cold parts and also economical for small sizes.
5. Better mechanical properties are achieved.

(c) Disadvantages/Limitations of Cold Working

1. Only small sized components can be easily worked as greater forces are required for large sections. Due to large deforming forces, heavy and expensive capital equipment is required.
2. The grain structure is not refined and residual stresses have harmful effects on certain properties of metals.
3. Many of the metals have less ductility e.g., carbon steel and certain alloy steels, cannot be cold worked at room temperature. It is therefore, limited to ductile metals and the range of shapes produced is not as wide as can be obtained by machining.
4. Tooling costs are high and as such it is used when large quantities of similar components are required.

2.4 FORGING

Forging can be defined as a method of shaping heated metal by compression. The forging process evolved from the manual art of simple blacksmithing. The special tools that a blacksmith use are various kinds of dies, swages and fullers.

Modern forging uses machine driven impact hammers or presses which deform the work piece by controlled pressure. The forging process is superior to casting as the parts formed by forging have denser microstructures, more defined grain patterns, and less porosity, making such parts much stronger than a casting. Forgings usually have great strength, as compared with other methods of producing products.

2.4.1 Forging Operations

Forging is the oldest metal working process. Because it just requires heating and hammering of metals, man found it easy. The following forging operations are performed.

Drawing down or swaging: The process of increasing length and decreasing cross sectional area of the metal is known as drawing. The compressive force (hammering or pressing) are applied perpendicular to the length axis of the metal piece.

Upsetting: It is just reverse of drawing. The cross-sectional area of the work piece is increased and length decreases. For it, the compressive forces are applied along the length axis of the metal piece.

Coining (closed-die forging): Minting of coins, where the slug is shaped in a completely closed cavity, is an example of closed-die forging. To produce the fine details of a coin, high pressures, and sometimes several operations are needed, while lubricants are not used because they can prevent reproduction of fine die surface details.

Heading (open-die forging): Heading is an example of open-die forging. It transforms a rod, usually of circular cross-section, into a shape with a larger cross-section. The heads of bolts, screws, and nails are some examples of heading. The work piece has a tendency to buckle if the length to- diameter ratio is too high.

Punching: It is the process of making holes by using punch.

Cogging: Also called drawing out, successive steps are carried to reduce the thickness of a bar. Forces needed to reduce the thickness of a long bar are moderate, if the contact area is small.

Fullering and Edging: It is an intermediate process to distribute the material in certain regions of the workpiece before it undergoes other forging processes that give it the final shape.

Roll Forging: A bar is passed through a pair of rolls with grooves of various shapes. This process reduces the cross-sectional area of the bar while changing its shape. This process can be the final forming operation. Examples are tapered shafts, tapered leaf springs, table knives, and numerous tools. Also, it can be a preliminary forming operation, followed by other forging processes. Examples are crankshafts and other automotive components.

Skew Forging: It is similar to roll forging but used for making ball bearings. A round wire is fed into the roll gap and spherical blanks are formed continuously by the rotating rolls.

2.4.2 Classification of Forging

Forging is classified into three categories:

1. Open-die Forging (Hand Forging, Power Forging)
2. Impression-die Forging
3. Closed-die Forging.

I. OPEN-DIE FORGING

Open-die forging is a hot forging process in which metal is shaped by hammering or pressing between flat or simple contoured dies (see Fig. 2.1). In open die forging the dies do not completely cover the workpiece. Instead, there are open spaces that allow various aspects of the workpiece to move from direct hot die contact, and to cooler open areas. In this type of forging, metals are worked above their recrystallization temperatures. Because the process requires repeated changes in workpiece positioning. The workpiece cools during open die forging below its hot-working or recrystallization temperature. It must be reheated before forging can continue.

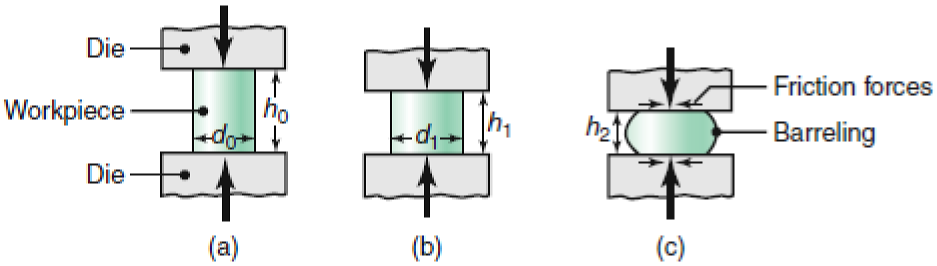


Fig 2.1 Open die Forging

(*a*) Operations performed on open die presses

1. Drawing out or reducing the cross-section of an ingot or billet to lengthen it.
2. Upsetting or reducing the length of an ingot or billet to a larger diameter.
3. Upsetting, drawing out, and piercing-processes sometimes combined with forging over a mandrel for forging rough-contoured rings. Practically all forgeable ferrous and non-ferrous

alloys can be open-die forged, including some exotic materials like age-hardening super alloys and corrosion-resistant refractory alloys.

(*b*) Applications

Open-die processes can produce:

1. Step shafts, solid shafts (spindles or rotors) whose diameter increases or decreases at multiple locations along the longitudinal axis.
2. Hollow cylindrical shapes, usually with length much greater than the diameter of the part Length, wall thickness, internal and outer diameter can be varied as needed.
3. Contour-formed metal shells like pressure vessels, which may incorporate extruded nozzles and other design features.

Open-die forging is further classified as hand forging and power forging:

(i) HAND FORGING

Sometimes called smithy or blacksmithing, hand forging is the simplest form of forging and it is one of the methods by which metal was first worked. The metal to be forged is first heated to red heat in the fire of a forge, and then is beaten into shape on a metal anvil with sledges or hammers.

Smith Forging Operations

In general, six basic types of forging operations exist:

1. Upsetting, or decreasing the length and increasing the diameter of the metal;
2. Swaging, decreasing the diameter of the metal;
3. Bending;
4. Welding, joining two pieces of metal together by semifusion;
5. Punching, the forming of small openings in the metal; and
6. Cutting out, the forming of large holes in the metal.

(i) Upsetting: A piece of metal, called the work, is upset when it is struck along the longest dimension (for example, the end of a rod or bar), which shortens and thickens it.

(ii) Swaging: It is accomplished by hammering the metal stock while it is held on the anvil within any one of various concave tools called swages.

(iii) Bending: It is accomplished either by hammering the work around a form or by leveraging it against a supporting fulcrum

(iv) Welding: In forge welding of iron, a flux such as borax is first applied to the heated metal to remove any oxides from the surfaces of the two pieces, and the pieces are then joined by hammering them together at high temperature. A welded joint of this kind, when properly made, is entirely homogeneous and is as strong and uniform, as the parent metal.

(v) Punching: To punch small holes, the work is supported on a ring shaped piece of metal above the anvil, and a punch of the proper shape is driven through the work by hammer blows.

(vi) Cutting: Larger holes are cut out, and portions of the work are cut off with heavy, sharp chisels similar to cold chisels which are used to cut cold metal.

Combinations of several of these operations can produce forgings of a wide variety of shapes.

Applications

Hand forging is used for making simple shapes such as chains, hooks, shackles, and agriculture equipment and tools.

(ii) POWER FORGING

It is used to produce large number of identical forgings. Machines which work on forgings by blow are called hammers and those which work by pressure are called presses.

II. ***IMPRESSION-DIE FORGING/PRECISION FORGING***

As the name implies, two or more dies containing impressions of the part shape are brought together, the workpiece undergoes plastic deformation until its enlarged sides touch the die side walls (see Fig. 2.3). During the process, flash is formed, as some of the molten metal from the workpiece flows outside the die impression. As the flash cools, it imparts deformation resistance to the workpiece, strengthening the final product. This builds pressure inside the bulk of the workpiece, aiding material flow into unfilled impressions. The finished part closely resembles the die impression. Because metal flow is restricted by the die contours, this process can yield more complex shapes and closer tolerances than open-die forging processes.

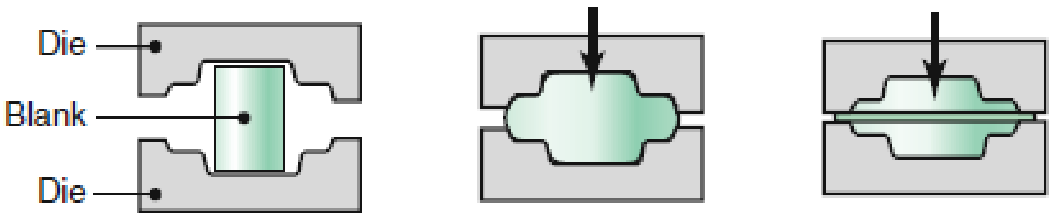


Fig. 2.3: Impression die forging

Most engineering metals and alloys can be forged via conventional impression-die processes, among them: carbon and alloy steels, tool steels, and stainless, aluminum and copper alloys, and certain titanium alloys.

Applications

1. Part geometry's range from some of the easiest to forge simple spherical shapes, block-like rectangular solids, and disc-like configurations to the most intricate components with thin and long sections that incorporate thin webs and relatively high vertical projections like ribs and bosses.
2. Although many parts are generally symmetrical, others incorporate all sorts of design elements (flanges, protrusions, holes, cavities, pockets, etc.) that combine to make the forging very non-symmetrical.
3. In addition, parts can be bent or curved in one or several planes, whether they are basically longitudinal, equidimensional or flat.

Impression die forging is further classified as drop, press and machine forging:

(i) Drop forging: It gets its name from the fact that the upper half of the die is dropped onto the lower half. Drop forgings are made by squeezing the metal at forging heat into shaped impressions cut in heavy steel blocks called dies. The job is divided equally in upper and lower die block. When the upper die block falls on the lower die, block metal is squeezed in the die cavity due to impact force. The die block falls from a height of 3 to 5 m. The bottom die block is held by set screws on to the base and top is raised by certain mechanism after its free fall. A workpiece may be forged by a series of punch and die operations (or by several cavities in the same die) to gradually change its shape.

The process involves several steps:

1. The first two steps are called fullering and edging. Here, the cross-sectional area of the metal is reduced in some areas and gathered in other areas. This also starts the fibrous grain flow.
2. The third step is referred to as blocking. The shape of the part is not pronounced hence, it may take several drops in the blocking cavity of the die. In step three, flash begins to appear.
3. The fourth step is called finishing. Here, the final shape of the part is completed.
4. The last step is called trimming. Holes are cleared and the flash is removed from the forging.

Drop forging requires machining to obtain dimensional tolerances and good surface finish.

(ii) Press forging: Press forging is a process similar to kneading, where a slow-continuous pressure is applied to the area to be forged. The pressure will extend deep into the material and can be completed either cold or hot. A cold press forging is used on a thin, annealed material, and a hot press forging is done on large work such as armor plating, locomotives and heavy machinery. In this type, only one blow is given as compared with number of blows in drop forging. In press forging number of stages are used and only in last stage die cavity is used to get finished forging. Dies may have less draft, and the forging comes nearer to the desired sizes. Press forging are shaped at each impression with a single smooth stroke and they stick to the die impression more rigidly. Unless some provision is made, the escape of air and excess die lubricant may be difficult. Thus, press-forging dies require a mechanical means for ejecting the forging.

Press forging are generally more accurate dimensionally than drop forging. The cost of the process is three to four times than that in drop forging but with press forging, unskilled labour can be used and production rate is higher. The working conditions with the press are better as there is no noise and vibrations.

(iii) Machine forging: The chief difference between hand forging and machine forging is that in the latter technique various types of machine powered hammers or presses are used instead of hand sledges. The power hammer can be mechanical or pneumatic type. The stroke of the hammer varies from 350 mm to 1000 mm and corresponding speeds range from 200 to 800 blows per minute. These machines enable the operator to strike heavy blows with great rapidity and thus to produce forgings of large size and high quality as swiftly as required by modern production-line methods. Another advantage of machine forging is that the heavier the blows struck during forging, the greater the improvement in the quality of metallic structure. Fine grain size in the forging, which is particularly desirable for maximum impact resistance, is obtained by working the entire piece. With large, hand-forged metal, only the surface is deformed, whereas the machine hammer or press will deform the metal throughout the entire piece.

Machine forging operations are frequently accomplished by use of a series of dies mounted on the same press or hammer. The dies are arranged in sequence so as to form the finished forging in a series of steps. After the piece has been partially formed by one stroke, it is moved to the next die for further shaping on the next stroke.

III. CLOSED-DIE FORGING

In closed-Die Forging, no flash is formed and the workpiece is completely surrounded by the dies (Fig. 2.4). In this process, a billet with carefully controlled volume is deformed (hot or cold) by a punch in order to fill a die cavity without any loss of material. Therefore, proper control of the volume of material is essential to obtain a forging of desired dimensions.

Undersized blanks in closed-die forging prevent the complete filling of the die, while oversized blanks may cause premature die failure or jamming of the dies.

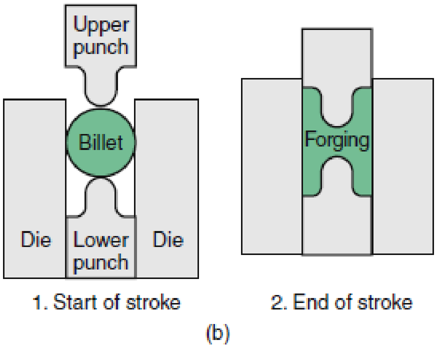


Fig. 2.4: Closed die forging.

Press used for closed-die forging is of two types:

(i) Hydraulic and

(ii) Mechanical.

A hydraulic press for closed-die forging has the same principle as that of a press for smith or flat-die forging except the construction of the dies.

In smith forging the press dies have flat surface, while in a closed-die forging the press dies have shaped impressions cut on dies. Moreover, they form an integral part of the frame to maintain accurate alignment of the dies.

Mechanical forging presses of the crank type have found wide application in forging practice. The operative units of the press are powered from motor mounted on the press frame. They are used for the production of rivets, screws, and nuts where a high operating speed is desired. In capacity, they range from 50,000 to 8,000,000 kg and speeds from 35 to 90 strokes per minute. Most engineering metals and alloys can be forged with closed die forging processes; among them are carbon and alloy steels, aluminum alloys and copper alloys.

Applications

Precision forgings, hollow forgings, fittings, elbows, tees, etc.

2.4.3. Forging Defects and Remedies

The common forging defects are:

1. Dirt, slag, blow holes: These are defects, resulting from the melting practice.

2. Seams, piping, cracks, scales or bad surface and segregation: These are ingot defects.
3. Decarburization: These defects result from improper heating of the forging.
4. Flakes: These defects result from improper cooling of the forging.
5. Fins and rags: These are small projections or loose metal driven into the forging surface.
6. Mismatch: This occurs due to improper alignment between the top and bottom forging dies.
7. Pitting: These are shallow surface depressions caused by scales which is not removed from dies.
8. Cold shut or laps: These are short cracks which usually occur at corners and at right angles to the surface. These are caused when the metal surface folds against itself during forging.
9. Dents: These arise due to careless work.
10. Unfilled section: It occurs when metal does not completely fill the die cavity.

Remedies

1. Shallow cracks and cavities can be removed by chipping out of the cold forging with pneumatic chisel or with hot sets during the forging processes.
2. Surface cracks and decarburized areas are removed from important forgings by grinding on special machines. Care should also be taken to see that the work piece is not under-heated, decarburized, overheated and burnt.
3. Die design should be properly made taking into consideration all relevant and important aspects that may impair forging defects and ultimate spoilage.
4. The parting line of a forging should lie in one plane to avoid mismatching.
5. Distorted forgings are straightened in presses, if possible.

2.4.4. Advantages of Forging

1. Directional strength: Forging produces predictable and uniform grain size and flow characteristics. These qualities translate into superior metallurgical and mechanical qualities, and deliver increased directional strength in the final part.

2. Structural strength: Forging also provides a degree of structural integrity that is unmatched by other metalworking processes. It eliminates internal voids and gas pockets that can weaken metal parts. Predictable structural integrity reduces part inspection requirements, simplifies heat treating and machining, and ensures optimum -part performance under field-load conditions.

3. Variety of sizes: Open die forged part weights can run from a single pound to over 400,000 pounds.

4. Variety of shapes: Shape design is just as versatile, ranging from simple bar, shaft and ring configurations to specialized shapes.

5. Metallurgical spectrum: Forgings can be produced from literally all ferrous and non-ferrous metals.

6. Material savings: Forging can measurably reduce material costs since it requires less starting metal to produce many part shapes.

7. Machining economies: Forging can also yield machining, lead time and tool life advantages.

8. Reduced rejection rules: By providing weld-free parts produced with cleaner forging quality material and yielding improved structural integrity, forging can virtually eliminate rejections.

9. Production efficiencies: Using the forging process, the same part can be produced from many different sizes of starting ingots or billets. This flexibility means that forged parts of virtually any grade can be manufactured more quickly and economically.

2.4.5. Limitations of Forging

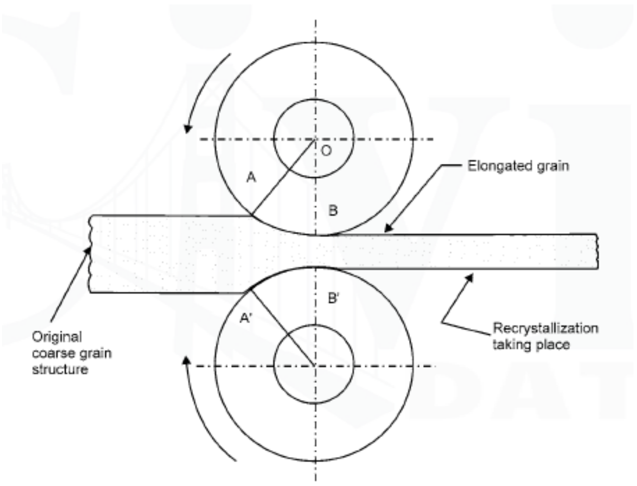
1. The forged parts often need to be machined before use.
2. Tooling for complicated geometry may be expensive and require multiple passes on the same workpiece.
3. The rapid oxidation of metal surfaces at high temperature results in scaling which wears the dies.
4. Initial cost of dies and maintenance cost is high.

2.4.6. Applications of Forging

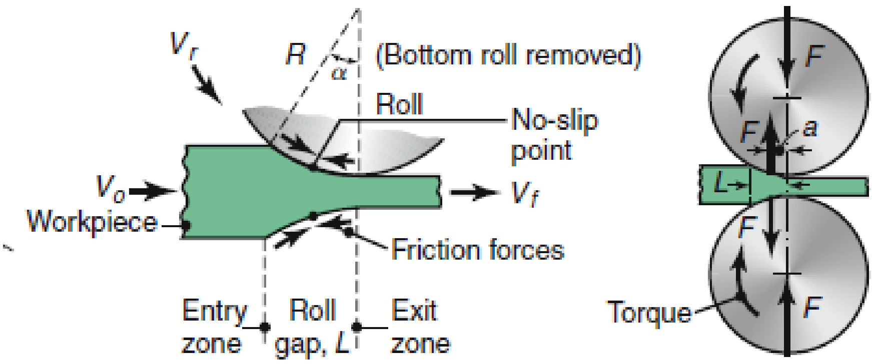
Typical parts made by forging are crankshafts and connecting rods for engines, turbine disks, gears, wheels, bolt heads, hand tools, and many types of structural components for machinery and transportation equipment.

2.5. ROLLING

It is the process of reducing the thickness or changing the cross-section of a long workpiece by compressive forces applied through a set of rolls. One effect of the hot working rolling operation is the grain refinement brought about by recrystallization, which is shown in Fig. 2.4. Coarse grain structure is broken up and elongated by the rolling action. Because of the high temperature, recrystallization starts immediately and small grains begin to form. These grains grow rapidly until recrystallization is complete. Growth continues at high temperatures, if further work is not carried on, until the low temperature of the recrystalline range is reached.



(a)



(b) (c)

Fig. 2.5. Hot-rolling Process

2.5.1. Principle of Rolling

In Fig. 2.5 (a) AB and A'B' are the contact arcs on the rolls. The wedging action on the work is overcome by the frictional forces that act on these arcs and draw the metal through the rolls. In the process of rolling, stock enters the rolls with a speed less than the peripheral roll speed. The metal emerges from the rolls travelling at a higher speed than it enters. At a point midway between A and B, metal speed is the same as the roll peripheral speed. Most deformation takes place in thickness, although there is some increase in width. Temperature uniformity is important in all rolling operations. Since it controls metal flow and plasticity. In rolling, the quantity of metal going into a roll and out of it is the same, but the area and velocity are changed.

In the process of becoming thinner, the rolled steel becomes longer and may become wider, but it is constrained by vertical rolls set to restrict this sideways growth. As the cross-sectional area is decreased, the velocity increases as does the length of the material. For example, a heated slab 18 cm thick weighing more than 12 tons is reduced to a coil of thin sheet in a matter of minutes.

2.5.2. Roll Force, Torque, and Power Requirements

The rolls apply pressure on the flat strip in order to reduce its thickness, resulting in a roll force, F, as shown in Fig. 2.5c. Note that this force appears in the figure as perpendicular to the plane of the strip, rather than at an angle. This is because, in practice, the arc of contact is very small compared with the roll radius, so we can assume that the roll force is perpendicular to the strip without causing significant error in calculations. The roll force in flat rolling can be estimated from the formula

$F = LwY_{avg}$

where L is the roll-strip contact length, w is the width of the strip, and Y_{avg} is the average true stress of the strip in the roll gap. Above is for a frictionless situation; however, an estimate of the actual roll force, including friction, may be made by increasing this calculated force by about 20%.

The torque on the roll is the product of F and a. The power required per roll can be estimated by assuming that F acts in the middle of the arc of contact; thus, in Fig. 2.5c, Therefore, the total power (for two rolls), in S.I. units, is

$$Power\ (in\ kW) = \frac{2\pi FLN}{60000}$$

where F is in newtons, L is in meters, and N is the revolutions per minute of the roll. In traditional English units, the total power can be expressed as

$$Power\ (in\ hp) = \frac{2\pi FLN}{33{,}000}$$

where F is in pounds and L is in feet.

2.5.3. Rolling Mill

A rolling mill consists of one or more roll stands, motor drive, reduction gears, and flywheel and coupling gears between units. The roll stand is the main part of the mill, where the rolling process is performed. It basically consists of housings in which bearings are fitted, which are used for mounting the rolls. Depending upon the profile of the rolled product, the body of the roll may be either flat for rolling sheets (plates or strips) or grooved for making structural members (channel, I-beam, rail).

Rolling mills are classified according to the number and arrangement of rolls in a stand (Fig. 2.6). They are classified as:

(A) For hot rolling of metals (Two-high rolling mill, Three-high rolling mill)

(B) For cold rolling of metals (Four high rolling mill, Cluster rolling mill)

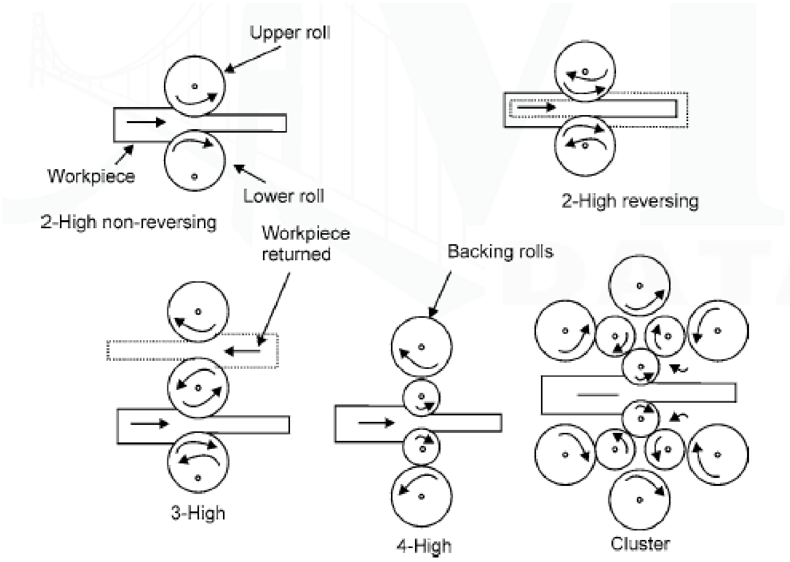


Fig. 2.6. Various roll arrangement used in rolling mills

(1) Two-high rolling mill: It is basically of two types i.e., non-reversing and reversing rolling mill. The two high non-reversing rolling stand arrangements is the most common arrangement. In this the rolls always move in only one direction, while in a two-high reversing rolling stand the direction of roll rotation can be reversed. This type of stand is particularly useful in reducing the handling of the hot metal in between the rolling passes. About 30 passes are required to reduce a large ingot into a bloom. This type is used in blooming and slabbing mills.

(2) Three-high rolling mill: It is used for rolling of two continuous passes in a rolling sequence without reversing the drives. After all the metal has passed through the bottom roll set, the end of the metal is entered into the other set of the rolls for the next pass. For this purpose, a table-tilting arrangement is required to bring the metal to the level with the rolls. Such type of arrangement is used for making plates or sections.

(3) Four-high rolling mill: It is generally a two-high rolling mill, but with small sized rolls. The other two rolls are the backup rolls for providing the necessary rigidity to the small rolls. It is used for both hot and cold rolling of wide plates and sheets.

(4) Cluster rolling mill: It uses backup rolls to support the smaller work rolls. In this type of mill, the roll in contact with the work can be as small as 1/4 in. in diameter. Foil is always rolled on cluster mills since the small thickness requires small-diameter rolls.

2.5.4. Roll Passes

The final rolled products such as plates, flats, sheets, rounds and sections are obtained in a number of passes starting from billet or slabs. For rolling the flat product, plain cylindrical rolls are used but for sections, grooved rolls are used. The type of grooving done is decided by the final section desired.

The roll pass sequence can be broadly classified into three types:

1. Breakdown passes: These are used for reducing the cross-sectional area nearer to what is desired. These would be the first to be present in the sequence.

2. Roughing passes: In these passes also, the cross-section gets reduced, but along with it, the shape of the rolled material comes nearer to the final shape.

3. Finishing passes: These are the final passes which give the required shape of pass follows a leader pass.

2.5.5. Defects in Rolling

There may be defects on the surfaces of the rolled plates and sheets or there may be structural defects within the material. The various defects are

(1) Surface defects may result from inclusions and impurities in the material, scale, rust, dirt, roll marks and other causes related to the prior treatment and working of the material. In hot rolling blooms, billets and slabs, the surface is usually preconditioned by various means, such as torch to remove scale.

(2) Structural defects are defects that distort or affect the integrity of the rolled product.

(3) Wavy edges are caused by bending of the rolls; the edges of the strip are thinner than the centre. Because the edges elongate more than the centre and are restrained from expanding freely, they buckle.

(4) Zipper cracks are usually caused by low ductility and barreling.

(5) Edge cracks are occurs in plates and slabs because of either limited ductility of metal or uneven deformation especially at the edges.

(6) Alligatoring is a complex phenomenon that results from inhomogeneous deformation of the material during rolling or from defects in the original cast ingot, such as piping. The workpiece splits along a horizontal plane on exit from the rolls.

2.5.6. Applications of Rolling

Rolling is used to produce components having constant cross-section throughout its length. The whole range of rolled products can be divided into the following types:

(a) Structural shapes or sections: This includes sections like round, square, hexagonal bars, channels, H and I beams and special sections like rail section. Fig. 4.13 shows some of the rolled structural shapes.

(b) Plates and sheets: These are produced of varying thickness.

(c) Special purpose rolled products: These include rings, balls, wheels and ribbed tubes

2.6 EXTRUSION

Extrusion is the process that forces metal to flow through a shape-forming die. The metal is plastically deformed under compression in the die cavity. Extrusion produces only compressive and shear forces in the stock without any tensile force, which makes high deformation possible without tearing the metal. It is a hot-working process which, like forging, rolling, etc., uses the good deformability of heated metallic materials for shaping them. A metal billet heated to the appropriate temperature is fed into the cylindrical container of the extrusion press and is forced by the action of a ram through a steel die whose orifice has the desired shape to produce the solid or hollow section (Fig. 2.7).

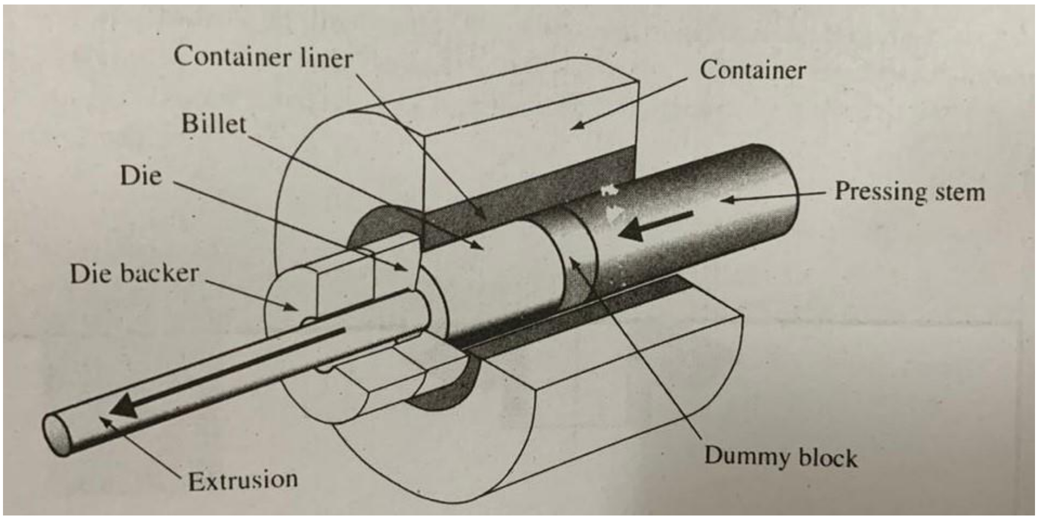


Fig 2.7: Extrusion Process

The metal emerges from the die as a continuous bar, which is cut to the required lengths. Extrusion products are therefore essentially linear in character, in the sense that shaping is confined to the cross-section only. The process is therefore eminently suitable for the production of bar-like and tubular objects. The cross-section that can be produced vary from solid round, rectangular, to L shapes, T shapes, tubes and many other different types. Extrusions, often minimize the need for secondary machining, but are not of the same dimensional accuracy or surface finish as machined parts. However, this process can produce a wide variety of cross-sections that are hard to produce cost-effectively using other methods.

Extrusion differs from drawing in that the metal is pushed, rather than pulled under tension. Extrusion processes can be carried on hot or cold.

Cold extrusion: Cold extrusion is the process done at room temperature or slightly elevated temperatures. This process can be used for most materials subject to designing robust enough tooling that can withstand the stresses created by extrusion. Cold extrusion can be used with any material that possesses adequate cold work ability–e.g., lead, tin, aluminum alloys, copper, titanium, molybdenum, vanadium, steel. Typical parts which are cold extruded are collapsible tubes, aluminium cans, cylinders, gear blanks.

The advantages of cold extrusion are:

1. No oxidation takes place.
2. Good mechanical properties due to severe cold working as long as the temperature created are below the recrystallization temperature.
3. Good surface finish with the use of proper lubricants.

Hot extrusion: Hot extrusion is basically a hot working process. It is done at fairly high temperatures, approximately 50 to 75% of the melting point of the metal. The pressures can range from 35-700 MPa. Due to the high temperatures and pressures and its detrimental effect on the die life as well as other components, good lubrication is necessary. The principal variables, which influence the force required to cause extrusion, are:

(1) The type of extrusion

(2) The extrusion ratio

(3) The working temperature

(4) The speed of deformation, and

(5) The frictional conditions at the die and container wall.

Typical parts produced by hot extrusion are trim parts used in automotive and construction applications, window frame members, railings, aircraft structural parts.

2.6.1. Types of Extrusion

Extrusion processes can be classified in five ways: Direct, Indirect, Combined, Hydrostatic and Impact.

1. Direct (forward) extrusion: Forward or direct extrusion is sometimes known as the Hooker process. In this process a ram forces the preheated billet through the die (see Fig. 2.8). The billet slides relative to the container wall; the wall friction increases the ram force considerably. A dummy block or pressure plate is placed at the end of the ram in contact with the billet. The process can be compared like squeezing toothpaste out of a tube. Using this method, it is possible to extrude LIP to SIX lengths from one die.

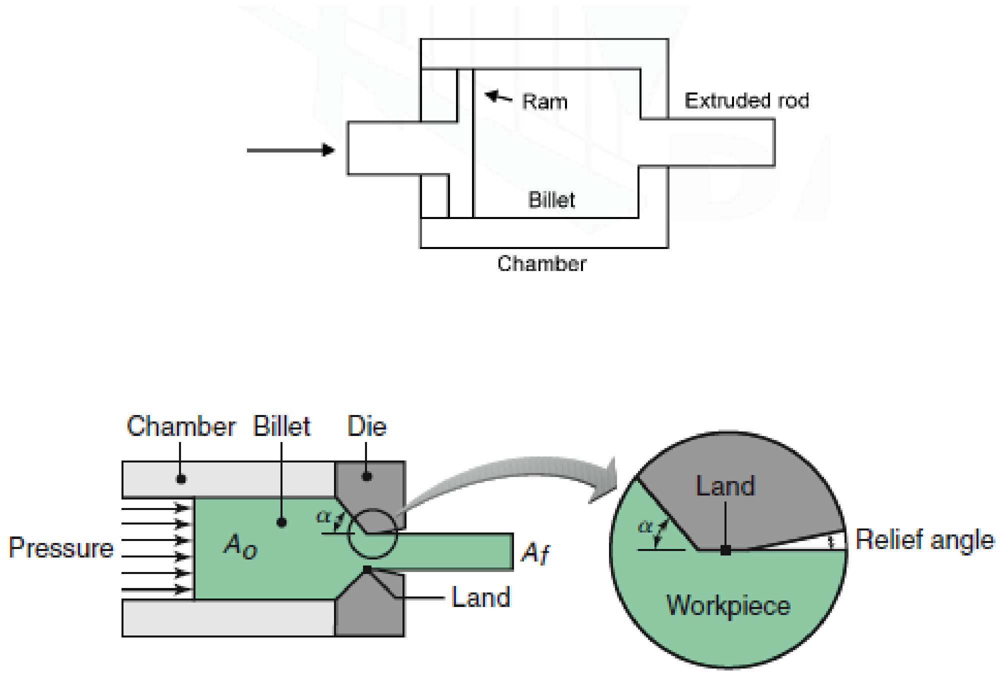


Fig. 2.8: Direct Extrusion

The process is generally used to produce profiled sections, thin-walled tubular parts with heavy flanges, straight tubular shapes, and hollow bar products. Typical products produced are bolts, screws or stepped shafts.

2. Indirect (reverse, inverted or backward) extrusion: Indirect extrusion is a process that forces the metal confined in the cavity to flow in a direction opposite to that of the ram travel (see Fig. 2.9).

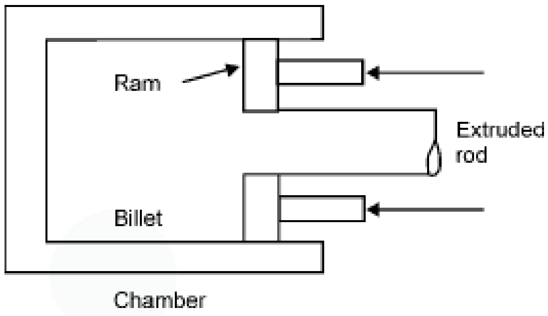


Fig. 2.9: Indirect Extrusion

Here, the die moves toward the billet; thus, except at the die, there is no relative motion at the billet-container interface. As a consequence, the frictional forces are lower and the power required for extrusion is less than for direct extrusion. In practice, a hollow ram carries a die, while the other end of the container is closed with a plate. Frequently, for indirect extrusion, the ram containing the die is kept stationary, and the container with the billet is made to move. Backward extrusion is useful in forming a variety of cylindrical shapes such as nuts, sleeves and tubular rivets.

3. Combined extrusion: Combined extrusion uses a combination of forward extrusion and backward extrusion. The metal is confined inside a matrix between the lower and upper punches. This forces the metal to flow both up and down. The extruded part is lifted from the die on the upward stroke of the slide by a lift out on the bed of the press. Some aspects of combined extrusion are:

1. It is fast
2. It can complete parts in few steps
3. It can produce large quantities with low unit costs
4. It wastes little material
5. It can make parts with small radii
6. It requires mirror tooling

4. Hydrostatic extrusion: In this process, the chamber is filled with a fluid that transmits the pressure to the billet, which is then extruded through the die. (Fig. 2.10) There is no friction along the walls of the container. Because the billet is subjected to uniform hydrostatic pressure, it does not upset to fill the bore of the container as it would in conventional extrusion. This means that the billet may have a large length to diameter ratio (even coils of wires can be extruded) or it may have an irregular cross section. Because of the pressurized fluid, lubrication is very effective, and the extruded product has good surface finish and dimensional accuracy.

Since friction is nearly absent, it is possible to use dies with very low semicone angle which greatly minimizes the redundant deformation. The only limitation with this process is the practical limit of fluid pressure that may be used because of the constraint involving the strength of the container and the requirement that the fluid does not solidify at high pressure.

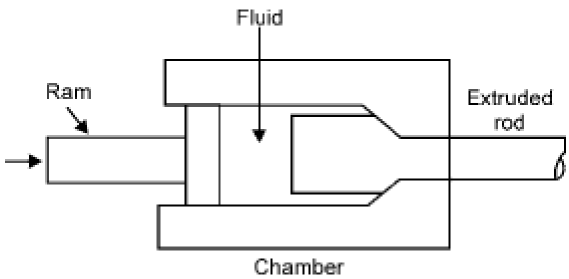


Fig. 2.10. Hydrostatic Extrusion

5. Impact extrusion: It is a form of indirect extrusion and is particularly suitable for hollow shapes. It is usually performed on a high-speed mechanical press. The punch descends at a high speed and strikes the blank, extruding it upwards (Fig. 2.11). The thickness of the extruded tubular section is a function of the clearance between the punch and the die cavity. Although the process is performed cold, considerable heating results from the high-speed deformation. Impact extrusion is restricted to softer metals such as lead, tin, aluminum and copper.

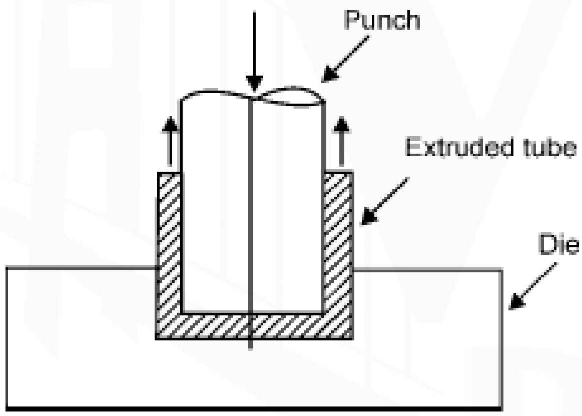


Fig. 2.11. Impact Extrusion.

2.6.2. Advantages of Extrusion

1. The tooling cost is low, as well as the cost due to material
2. Intricate cross sectional shapes, hollow shapes and shapes with undercuts can be produced.
3. The hardness and the yield strength of the material are increased.
4. In most applications, no further machining is necessary.

2.6.3. Limitations of Extrusion

1. High tolerances are difficult to achieve.
2. The process is limited to ductile materials.
3. Extruded products might suffer from surface cracking. It might occur when the surface temperature rise significantly due to high extrusion temperature, friction, or extrusion speed.
4. Internal cracking might also occur. These cracks are attributed to a state of secondary tensile stresses at the centre line of the deformati on zone in the die.
5. For a small extusion ratio and large die angle, the centre of the extrusion is not directly deformed, but dragged along by the stretching outer surface material. This generates tensile stresses in the core which can lead to 'arrow-head' failure or centre-burst detects.

2.7 SHEARING

Before a sheet-metal part is made, a *blank* of suitable dimensions first is removed from a large sheet (usually from a coil) by *shearing*. This sheet is cut by subjecting it to shear stresses, generally using a punch and a die (Fig. 2.12a). The typical features of the sheared edges of the sheet and of the slug are shown in Fig. 2.12b and c, respectively. Note that the edges are not smooth nor are they perpendicular to the plane of the sheet.

Shearing generally starts with the formation of cracks on both the top and bottom edges of the workpiece (at points *A* and *B*, and *C* and *D*, in Fig. 2.12a). These cracks eventually meet each other and complete separation occurs. The rough *fracture surfaces* are due to the cracks; the smooth and shiny *burnished surfaces* on the hole and the slug are from the contact and rubbing of the sheared edge against the walls of the punch and die, respectively.

The major processing parameters in shearing are

- The shape of the punch and die
- The speed of punching
- Lubrication
- The **clearance**, *c*, between the punch and the die.

The clearance is a major factor in determining the shape and the quality of the sheared edge. As the clearance increases, the zone of deformation (Fig. 2.13a) becomes larger and the sheared edge becomes rougher. The sheet tends to be pulled into the clearance region, and the perimeter or edges of the sheared zone become rougher. Unless such edges are acceptable as produced, secondary operations may be required to make them smoother (which will increase the production cost). Edge quality can be improved with increasing punch speed; speeds may be as high as 10 to 12 m/s (30 to 40 ft/s.

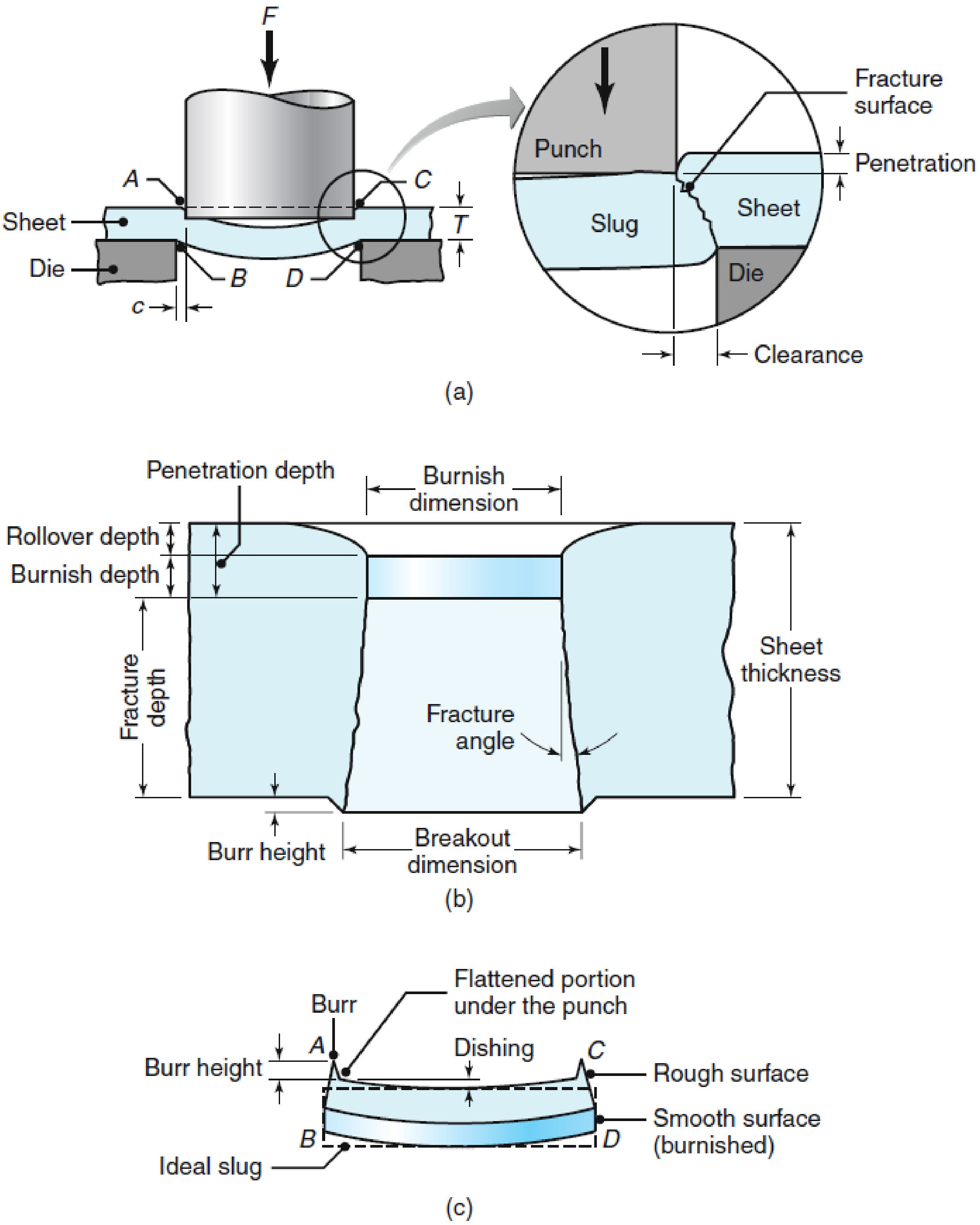


Fig. 2.12. (a) Schematic illustration of shearing with a punch and die, indicating some of the process variables. Characteristic features of (b) a punched hole and (c) the slug. (Note that the scales of (b) and (c) are different.)

As shown in Fig. 2.13b, sheared edges can undergo severe cold working due to the high shear strains involved. Work hardening of the edges then will reduce the ductility of the edges and thus adversely affect the formability of the sheet during subsequent operations, such as bending and stretching. The ratio of the burnished area to the rough areas along the sheared edge (a) increases with increasing ductility of the sheet metal and (b) decreases with increasing sheet thickness and clearance. The extent of the deformation zone in Fig. 2.13 depends on the punch speed. With increasing speed, the heat generated by plastic deformation is confined to a smaller and smaller zone. Consequently, the sheared zone is narrower, and the sheared surface is smoother and exhibits less burr formation.

A burr is a thin edge or ridge, as shown in Fig. 2.12 b and c. Burr height increases with increasing clearance and ductility of the sheet metal. Dull tool edges contribute greatly to large burr formation. The height, shape, and size of the burr can significantly affect subsequent forming operations.

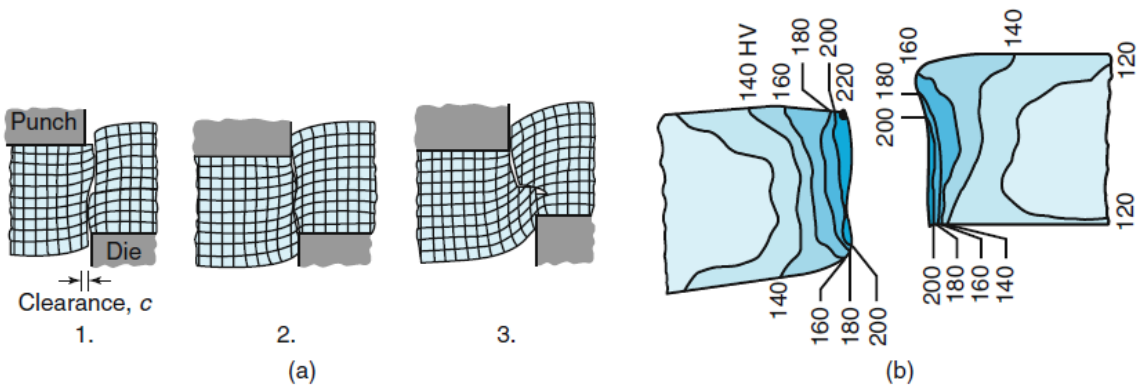


Fig. 2.13. (a) Effect of the clearance, c, between punch and die on the deformation zone in shearing. As the clearance increases, the material tends to be pulled into the die rather than be sheared. In practice, clearances usually range between 2 and 10% of the thickness of the sheet. (b) Microhardness (HV) contours for a 6.4-mm (0.25-in.) thick AISI 1020 hot-rolled steel in the sheared region.

2.7.1. Punch Force. The force required to punch out a blank is basically the product of the shear strength of the sheet metal and the total area being sheared along the periphery. The *maximum punch force*, *F*, can be estimated from the equation

$$F = 0.7TL(\text{UTS}),$$

where T is the sheet thickness, L is the total length sheared (such as the perimeter of a hole), and UTS is the ultimate tensile strength of the material. As the clearance increases, the punch force decreases, and the wear on dies and punches also is reduced. Friction between the punch and the workpiece can, however, increase punch force significantly. Furthermore, in addition to the punch force, a force is required t strip the punch from the sheet during its return stroke. This second force, which is in opposite direction of the punch force, is difficult to estimate because of the many factors involved in the operation.

Example: Estimate the force required for punching a 1-inch (25-mm) diameter hole through a $\frac{1}{8}\,inch$ (3.2-mm) thick annealed titanium-alloy Ti-6Al-4V sheet at room temperature.
Solution: The force is estimated from Eq. (16.1), where the UTS for this alloy is found from Table 6.10 to be 1000 MPa or 140,000 psi.

F = 0.7 $\left(\frac{1}{8}\right)(\pi)(1)(140{,}000)$ = 38,500 lb = 19.24 tons = 0.17 MN.

2.7.2. Shearing Operations

The most common shearing operations are **punching**—where the sheared slug is scrap (Fig. 2.14 a) or may be used for some other purpose—and **blanking**—where the slug is the part to be used and the rest is scrap. The operations described next, as on computer-numerical-controlled machines with quick-change toolholders. Such machines are useful, particularly in making prototypes of sheet-metal parts requiring several operations to produce.

Die Cutting. This is a shearing operation that consists of the following basic processes (Fig. 2.14b):
• **Perforating**: punching a number of holes in a sheet
• **Parting**: shearing the sheet into two or more pieces
• **Notching**: removing pieces (or various shapes) from the edges
• **Lancing**: leaving a tab without removing any material.
Parts produced by these processes have various uses, particularly in assembly with other components. Perforated sheet metals with hole diameters ranging from around 1 mm (0.040 in.) to 75 mm (3 in.) have uses as filters, as screens, in ventilation, as guards for machinery, in noise abatement, and in weight reduction of fabricated parts and structures.

2.7.3. Characteristics and Type of Shearing Dies

Clearance. Because the formability of the sheared part can be influenced by the quality of its sheared edges, clearance control is important. The appropriate clearance depends on

- The type of material and its temper
- The thickness and size of the blank
- Its proximity to the edges of other sheared edges or the edges of the original blank.

Clearances generally range between 2 and 8% of the sheet thickness, but they may be as small as 1% (as in fine blanking) or as large as 30%. The smaller the clearance, the better is the quality of the edge. If the sheared edge is rough and not acceptable, it can be subjected to a process called **shaving,** whereby the extra material from the edge is trimmed by cutting. As a general guideline, (a) clearances for soft materials are less than those for harder grades; (b) the thicker the sheet, the larger the clearance must be; and (c) as the ratio of hole diameter to sheet thickness decreases, clearances should be larger. In using larger clearances, attention must be paid to the rigidity and the alignment of the presses, the dies, and their setups.

Punch and Die Shape. Note in Fig. 2.13a that the surfaces of the punch and of the die are both flat. Because the entire thickness is sheared at the same time, the punch force increases rapidly during shearing. The location of the regions being sheared at any particular instant can be controlled by *beveling* the punch and die surfaces. This shape is similar to that of some paper punches, which you can observe by looking closely at the tip of the punch.

Compound Dies. Several operations on the same sheet may be performed in one stroke at one station with a *compound die* (Fig. 2.14). Such combined operations usually are limited to relatively simple shapes, because (a) the process is somewhat slow and (b) the dies rapidly become much more expensive to produce than those for individual shearing operations, especially for complex dies.

Progressive Dies. Parts requiring multiple operations to produce can be made at high production rates in *progressive dies*. The sheet metal is fed through as a coil strip, and a different operation (such as punching, blanking, and notching) is performed at the same station of the machine with each stroke of a series of punches (Fig. 2.14c). An example of a part made in progressive dies is shown in Fig. 2.14d; the part is the small round piece that supports the plastic tip in spray cans.

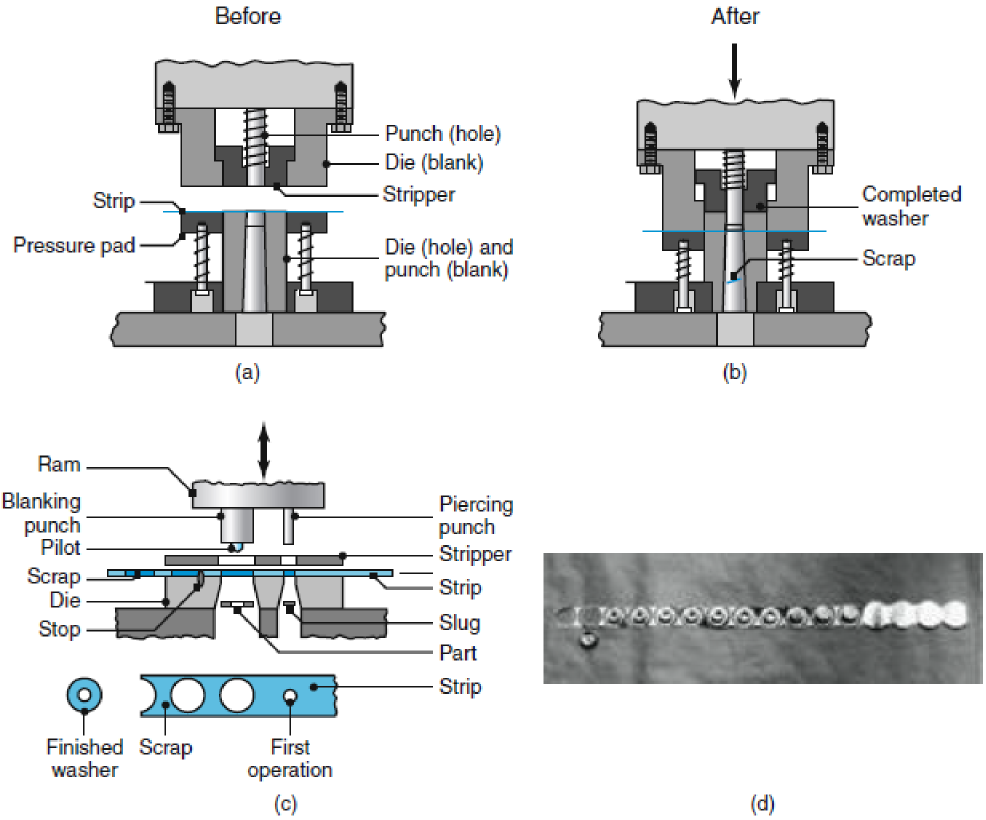


FIGURE 2.14 Schematic illustrations (a) before and (b) after blanking a common washer in a compound die. Note the separate movements of the die (for blanking) and the punch (for punching the hole in the washer). (c) Schematic illustration of making a washer in a progressive die. (d) Forming of the top piece of an aerosol spray can in a progressive die. Note that the part is attached to the strip until the last operation is completed.

Transfer Dies. In a *transfer-die* setup, the sheet metal undergoes different operations at different stations of the machine that are arranged along a straight line or a circular path. After each step in a station, the part is transferred to the next station for further operations.

Tool and Die Materials. Tool and die materials for shearing generally are tool steels and (for high production rates) carbides. Lubrication is important for reducing tool and die wear, thus improving edge quality.

2.7.4. Miscellaneous Methods of Cutting Sheet Metal

There are several other methods of cutting sheets and, particularly, plates:

• **Laser-beam cutting** is an important process typically used with computer-controlled equipment to cut a variety of shapes consistently, in various thicknesses, and without the use of any dies. Laser-beam cutting also can be combined with punching and shearing. These processes cover different and complementary ranges. Parts with certain features can be produced best by one process; some with other features can be produced best by the other process. Combination machines incorporating both capabilities have been designed and built.

- **Water-jet cutting** is effective on many metallic as well as nonmetallic materials.
- Cutting with a **band saw**; this method is a chip-removal process.
- **Friction sawing** involves a disk or blade that rubs against the sheet or plate at high surface speeds.
- **Flame cutting** is another common method, particularly for thick plates; it is used widely in shipbuilding and on heavy structural component.

2.8. HIGH ENERGY RATE FORMING PROCESSES

In all the metal forming processes we have discussed, the conventional energy sources are used. In addition to these, energy sources such as chemical, magnetic, and electrical discharge can be used. Since, in all such processes, the rate of energy flow is of a much higher order, these are commonly called high-energy-rate (HER) processes. As the kinetic energy of a moving body is proportional to the square of its velocity, a large amount of energy can be supplied by a relatively smaller body moving at a high speed. For example, a press of capacity 500 kN moving over a distance of 0.15 m delivers an energy of 75 kJ. Approximately the same amount of energy can be delivered by a hammer weighing 42 kN if it strikes the workpiece with a velocity of 6 m/sec. However, a water front, weighing only 26 N, made to move with a velocity as high as 240 m sec by an explosive charge, can supply the same amount of energy. This principle can be used in making small machines and equipment. Now, let us consider the rate of energy release in the three cases we have mentioned. In the first case, the typical time consumed is about 0.5 sec, indicating a power of 150 kW. The drop hammer takes about 0.06 sec to come to rest and the power involved turns out to be 1.25 MW. The explosive operation is completed in about 0.0007 sec, implying a power of 107 MW. This indicates that the last case results in not only the most compact but also the most powerful machine. High velocity forming operations, viz., explosive and electric discharge forming, are based on the foregoing principle.

We now discuss the three common HER processes.

2.8.1. Explosive Forming

Figure 3.60 shows two schemes of explosive forming. In both, a shock wave in the fluid medium (normally water) is generated by detonating an explosive charge. For a small part, the entire shock wave front is utilized in a confined space, whereas for a large object, only a part of the wave front is used. Obviously, the unconfined operation is less efficient. However, there is a greater hazard of die failure in the confined operation due to the inevitable lack of control in explosive forming.

The typical explosives include TNT and dynamite for higher energy,

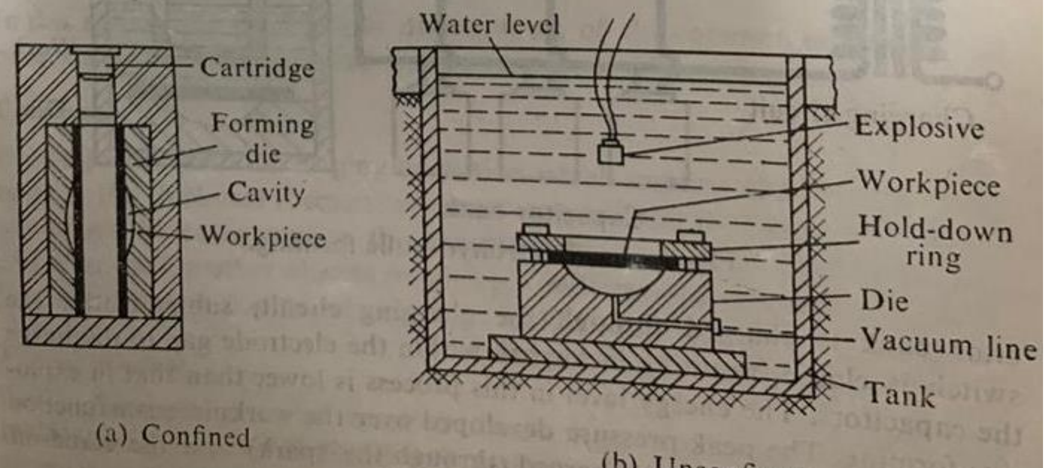


Fig. 3.60 Explosive forming.

and gun powder for lower energy. With high explosives placed directly over the workpiece, pressures up to 35 kN/mm^2 can be generated. With low explosives, pressures are limited to 350 N/mm^2.

With water as the transmitting medium, the peak pressure p obtained is given by

$$p = CW^{n/3}D^{-n} \text{ N/mm}^2, \tag{3.107}$$

where W is the weight of the explosive in newtons and D is the distance of the workpiece from the explosive (stand-off distance) in cm. The typical value of n is around 1.15. The constant of proportionality C has varying values for different types of explosives, as given here:

	Pentolite	TNT	Tetryl
C	4500	4320	4280

The distance between the explosive charge and the free surface of water (in unconfined forming) should be at least twice the stand-off distance. Otherwise much energy is lost, lowering down the efficiency of the operation. Using various types of tooling, we can form a variety of shapes. Generally, the effects of the process on material properties are similar to those in conventional forming.

2.8.2. Electrohydraulic Forming

Electric discharge in the form of sparks, instead of explosives, can also be used to generate a shock wave in a fluid. An operation using this principle of generating a shock wave is called electrohydraulic forming. The characteristics of this process are very similar to those of explosive forming. Figure 3.61 shows the basic scheme of electrohydraulic forming. The capa-

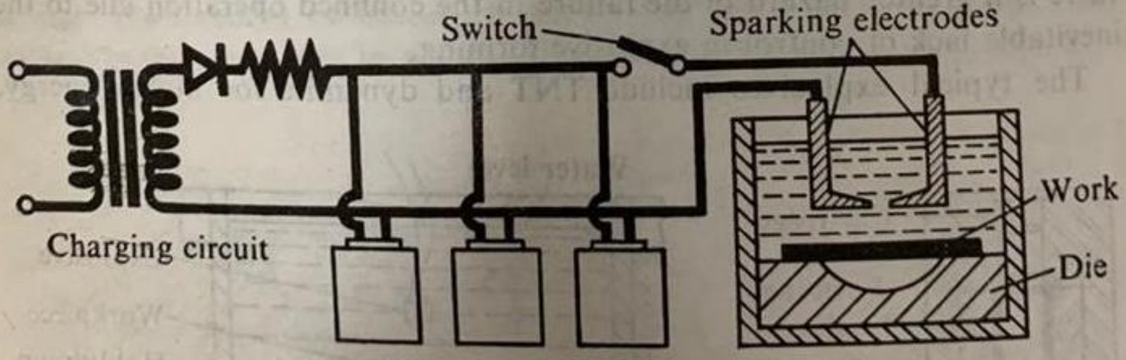


Fig. 3.61 Electrohydraulic forming.

citor bank is charged through the charging circuit; subsequently, the switch is closed, resulting in a spark within the electrode gap to discharge the capacitors. The energy level in this process is lower than that in explosive forming. The peak pressure developed over the workpiece is a function of the amount of energy discharged (through the spark) and the stand-off distance.

2.8.3. Electromagnetic Forming

Just as in electrohydraulic forming, so too in electromagnetic forming, the electrical energy is first stored in a capacitor bank. This energy is then discharged through a coil by closing the switch (Fig. 3.62). The coil produces

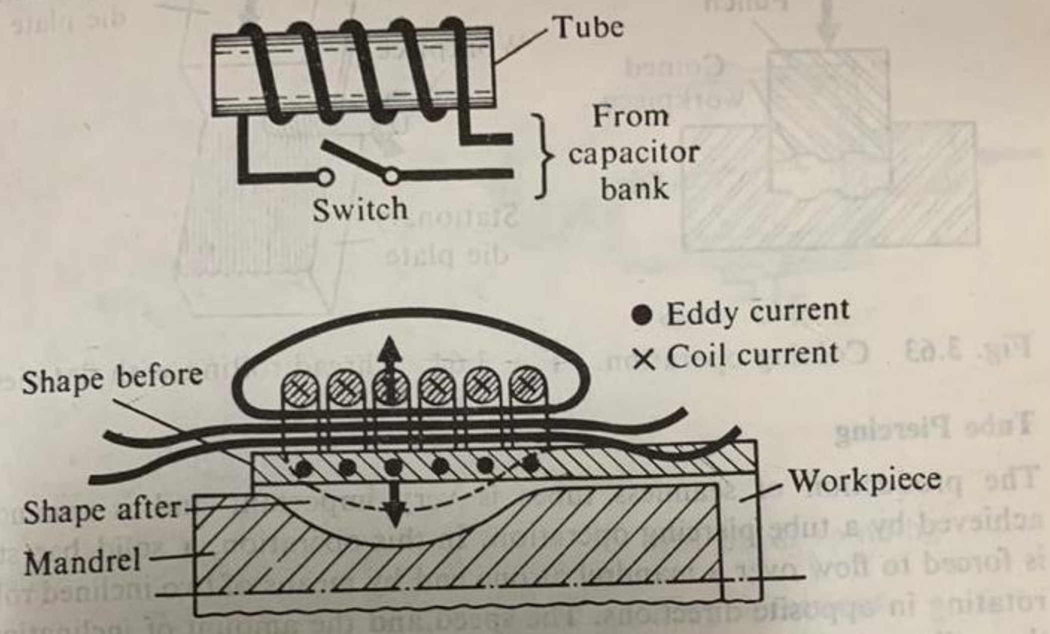


Fig. 3.62 Electromagnetic forming.

a magnetic field; the intensity of this field depends on the value of the current. Since the metallic workpiece is in this magnetic field (varying with time), a current is induced in the job which sets up its own magnetic field. The directions of these fields are such that the rigidly-held coil repels the workpiece into the die. The workpiece obviously has to be electrically conductive but need not be magnetic. Short life of the coil is the major problem in such an operation.