
If the shape of a metal is permanently altered by a force or pressure we call the process forming. There are many ways of forming metal. The list below contains the most commonly used in manufacturing.

- Extrusion
- Drawing
- Spinning
- Rolling
- Forging

There are two methods of carrying out these forming processes.

1. Cold Working
2. Hot Working

The distinction between the two methods is linked to the recrystallisation temperature of the metal being worked.

If the process is carried out at below recrystallisation temperature it is called cold working. Performed at a temperature even slightly below recrystallisation it will still be cold working. The fact that the metal can be quite hot is irrelevant.

If the process is carried out at above recrystallisation it is termed hot working.

Cold Working

As already stated this may be carried out at temperatures ranging from room temperature to just below recrystallisation. The resulting work hardening changes many of the metal's properties.

Hardness, yield point and strength are increased while ductility, density and electrical conductivity are reduced, the latter two only slightly.

When we were dealing with deformation of crystalline materials by cold working in Topic 4 we saw that as deformation progressed the "clogging" of slip and twin planes caused a steady increase in resistance by the metal to further deformation. We called this build-up of resistance Strain or Work Hardening.

The effect of work hardening is to develop in the distorted crystals and grains higher than normal energy levels. While most of the applied energy for deformation is dissipated as heat, 10% to 15% remains as stored energy in the distorted grains. The atoms are trying to move back to their unstrained lattice positions but are prevented by the high energy levels contained in the slip dislocations.
If the energy level of the atoms is increased by the application of
heat, they will overcome the slip dislocation energy and move back to
their original lattice positions.

This process of heating a work hardened crystalline material to relieve
the internal stresses is called **Annealing**.

Forming processes such as drawing and stretching which use tensile
forces employ the cold working method. Metal at high temperature is
weak in tension and would fail under hot working.

**ADVANTAGES:**

(i) Dimensional accuracy.
(ii) Clean smooth finish.
(iii) Surface toughness.
(iv) Increased hardness and yield strength.

**DISADVANTAGES:**

(i) Reduced ductility.
(ii) Expensive due to the greater power
required and the more sophisticated
dies and equipment needed.
(iii) Slight decrease in electrical
conductivity and density.

Figure 1 shows the distorted stressed grains resulting from cold
rolling.

![Figure 1](image)

**ANNEALING**

When the annealing process is complete the material will have regained
its original levels of ductility, malleability etc.

Annealing takes place in 3 stages.

1. The initial rise in temperature releases some of the stored
energy resulting from the work done during grain deformation.
There is a slight movement of some atoms towards their original
lattice positions. At this stage some of the internal stress
has been relieved but strength and hardness have been retained.

2. With further temperature rises the increased atom movement
allows released atoms to form nuclei at grain boundaries and
along slip planes. These nuclei develop into crystals by
absorbing more atoms as they are released from the distorted
grains.
The temperature at which nuclei form and begin developing into crystals is called that metal's Recrystallisation Temperature.

3. With either the maintenance of the recrystallisation temperature or further increases in temperature, the crystals develop into grains by absorbing all the atoms as they are released from the cold worked distorted structure. When this grain regrowth is complete the result is unstressed equiaxed grains.

The metal properties will have returned to what they were before cold working.

Grain size after annealing depends on the amount of deformation, the annealing temperature and the time allowed for the process.

Figure 2 shows diagrammatically the stages of recrystallisation from cold worked to stress free (annealed).

![Stressed grains in cold rolled metal.](image)

![Nuclei forming at grain boundaries and slip plane positions.](image)

![Growth of new crystals from nuclei.](image)

![Further crystal growth.](image)

![Advanced regrowth. Very little left of original grains.](image)

![Recrystallisation complete.](image)

**Fig. 2.**

**HOT WORKING**

As we have seen, when a metal is cold worked internal stresses are set up causing it to become work hardened. When the optimum level of work hardening has developed the metal must be annealed before further deformation or failure will occur.

Hot working combines deformation and annealing into the one continuous process. Because the metal is being worked above its recrystallisation temperature the resulting stressed and distorted grains are being simultaneously annealed. This allows the forming process to continue to conclusion uninterrupted.
ADVANTAGES: 
(i) Relatively low levels of energy required.
(ii) Less sophisticated tools and equipment needed.
(iii) Continuous operation.

DISADVANTAGES: 
(i) Poor surface finish due to scaling and oxidation.
(ii) Poor dimensional accuracy.
(iii) Difficulties in handling hot materials.
(iv) Heating apparatus required.

It should be noted that the recrystallisation results in a finer grain structure so the material will be tougher, stronger and more ductile than the original casting.

Figure 3 shows diagrammatically the deformation, recrystallisation and grain regrowth in a hot rolling process.

![Diagram of hot rolling process](image)

It is common practice to combine the two methods.

Hot working is used first to quickly reduce the original cast billet to slightly oversized dimensions. The worked surfaces are then cleaned of oxide scale and the finished dimensions are achieved by cold working to give surface finish and toughness, improved tensile strength etc.

FAILURE OR FRACTURE

As we have seen in Topic 4 when deformation increases to the point where work hardening has reached its limit, further application of stress will result in failure or fracture.

If failure occurs after extensive deformation it is called ductile failure.

e.g. Annealed aluminium and copper, lead, mild steel etc.

If failure occurs after little or no deformation it is called brittle failure.

e.g. Work hardened aluminium and copper, hardened medium and high carbon steels, cast iron etc.
Temperature plays a significant role in the fracture of metals. From Table 1, Topic 5, zinc, lead and tin change from ductile to brittle failure only at very low temperatures.

In all metals and alloys there is a temperature where failure can occur equally either across grains or along grain boundaries. This temperature is called the metal's equi-cohesive temperature and it varies from metal to metal depending on their melting points.

Below this temperature, failure occurs across grains, above it failure follows grain boundaries.

The rate at which deformation occurs also affects failure in a crystalline material.

We can summarise this by saying:

*Decreased strain rate and increased temperature produces failure along grain boundaries, whereas, increased strain rate and decreased temperature tend to produce failure across the grains. (See Figure 4)*

![Figure 4](#)

**FORMING METHODS**

1. **EXTRUSION**

Extrusion is the term used to describe the metal-forming process which uses pressure on a billet of metal in a container to force it through or around a die.

The action of squeezing toothpaste from a tube is an example of extrusion.

The extruded material takes the shape of the hole cross-section in the die. See Figure 5.

![Figure 5](#)
There are TWO methods of extrusion:

(a) IMPACT

(b) THROUGH DIE.

(A) IMPACT

This is the method used to form aluminium drink cans, toothpaste tubes and similar shapes.

A billet of metal or slug is placed in a die and a ram strikes the billet forcing the metal to "flow" up into the gap between the ram and the inside of the die, this being the only way of "escape" for the metal under pressure.

As Figure 6 shows, the metal "flows" up the side of the ram beyond the die height. The top edge of the formed can is trimmed in a later process.

Lead, tin and aluminium alloys are suitable for extrusion by this method. Lead and tin may be extruded at room temperature but aluminium alloy slugs should be preheated to 200° - 250° immediately prior to forming. The heat generated by impact is sufficient to raise lead and tin to the plasticity level necessary for forming to take place.

The diameter of the ram determines the inside diameter of the can and the gap between the inside of the die and the ram determines the wall thickness.

(B) THROUGH DIE

This method is used to produce a variety of cross-sectional shaped bars, rods and tubing. The billet is positioned in the container and a ram forces the metal through a hole in the die. The hole shape is the same as the desired cross-section of the bar.

Through die extrusion may be direct or indirect. The difference between the two methods is the relative directions of the ram and the extrusion.
Figure 7 (a) shows an example of direct extrusion. The ram forces the billet directly through the die so that the ram and the extrusion are travelling in the same direction.

Figure 7 (b) shows an example of indirect extrusion. In this method the die is attached to the ram and moves with it to force the billet against the closed end of the container. The pressure forces the billet back through the die and through a clearance hole in the ram. The extrusion moves in the opposite direction to the ram.

For tube extrusion a mandrel, of the same cross-section as the desired tube hole, is used in conjunction with the ram.

The ram and mandrel can be either in one piece (fixed mandrel) or operated independently (floating mandrel).

For each type of mandrel the billet may be either cast with a hole along its axis or an axial hole bored out prior to extrusion. This hole accommodates the mandrel during extrusion.

The use of a hollow billet can cause weaknesses or imperfections at the inside surface of the tube due to oxidation during preheating. This can be avoided by using the mandrel to pierce the preheated billet before the ram exerts the extrusion pressure. Figure 8 shows details of the two steps.

The mandrel shape determines the shape of the hole in the tube.
Metals suitable for extrusion are lead, brass, bronze, copper, aluminium and its alloys and magnesium alloys. The relatively low yield strengths and plasticity temperatures for the above metals make them suitable for extrusion.

While steel can be extruded the pressure and temperatures required and the tendency of the billet to "weld" to the walls of the container make it both difficult and expensive. Phosphate salts or glass coating on the billets, which melt under heat and pressure and act as lubricants, will minimise the problem of welding when steel is extruded.

For through die extrusion the billets should be preheated to near recrystallisation levels.

The forces required for extrusion depend on both the metal being extruded and the size of the extrusion. These forces can vary from 10 MN to 100 MN.

Extrusion is a relatively cheap way of forming metals, especially when large numbers of the product are required. A high level of dimensional accuracy and surface finish is a feature of this forming method.

2. DRAWING

This is a process which also employs force and suitably shaped dies to form metal to shape. The force can be either push (compressive) or pull (tensile).

Metals suitable for drawing must have a low yield strength and high ductility. Such metals as low carbon steel, copper and some of its alloys and aluminium and some of its alloys are commonly used.
Drawing is almost always performed cold, that is below the metal's recrystallisation temperature. The only time hot drawing is employed is for thick-walled gas cylinders, tanks and tubing or prior to cold drawing.

In all forms of drawing the metal is either forced through a suitably shaped hole in a die or shaped between the male and female halves of a die.

**COLD DRAWING**

As previously stated almost all drawing is performed below recrystallisation. Such items as small cups, car body parts (mudguards, bonnets, door panels), thin tubing, rods, bars, wire etc., are all formed by the cold drawing process.

Cups, body parts and the like are formed by pressing the sheet metal between the two parts of a suitably shaped die.

Depending on the degree of deformation this process is sometimes called deep drawing and can require more than one operation. It is usually performed slowly. See Figure 9.

![Fig. 9.](image)

Tubing, rods, bars, wire etc., are formed by pulling the material through a suitably shaped hole in a die. For this type of product the material must be first prepared to slightly oversize either by hot drawing, extrusion or rolling. The material is then drawn successively through a series of dies to obtain the final shape.

Each run through the set of dies is called a "pass". It may be necessary to anneal the material between each pass due to the work hardening effect of cold working.

Figure 10 shows a typical container holding the hardened die used for wire drawing.

![Fig. 10.](image)
Metal for spinning must have high ductility and low yield strength.

For extensive forming some work hardening of the metal can occur and this will require relief by annealing before the job can be completed.

This process achieves similar results to deep drawing but uses cheap equipment and simple methods. It is very suitable when only a few components are required.

The speed of rotation varies greatly from relatively slow (300 - 400 R.P.M.) for heavy gauge stronger metals to quite fast (1500 - 2000 R.P.M.) for the lighter low yield ones.

Although spinning has been traditionally carried out manually, in recent times machine spinning methods have been developed for heavy gauge materials and quantity production.

**GENERALLY SPEAKING:**

Using cold working processes, the technician can produce the required combination of such properties as toughness, hardness, strength, ductility and machinability.

These are achieved by the die shape restricting and directing the metal's grain flow during the operation.

Such properties cannot be produced or controlled in items which are machined to shape.
The structure on which this type of drawing is carried out is called a draw bench. A gripping device, called a "dog" is fastened to the "tagged" end of the material protruding through the die and when in operation the "dog" travels on rails, fixed to the bench, drawing the material through the die.

The dies are usually made from very hard material (tungsten carbide) and the surfaces of the tapered hole are ground and polished smooth. Lubricant is used for the operation.

**ADVANTAGES:**

(i) High level of dimensional accuracy and surface finish.
(ii) No need for heating.
(iii) Improved strength and directional properties due to work hardening.
(iv) Quick process for the single step drawing of car body parts etc.

**DISADVANTAGES:**

(i) Sturdy equipment and large forces are required.
(ii) Metal surfaces must be thoroughly cleaned of scale etc. before drawing is commenced.
(iii) Processes of wire, rod and tube drawing are slow resulting from the repeated annealing and cleaning steps due to work hardening.

3. **SPINNING**

A cold working process which forms a flat disc of sheet metal into such shapes as dishes, bowls, cooking utensils, musical instrument parts, lamp reflectors etc.

A former block, usually made from hardwood, is set up in a lathe chuck. This block is the male equivalent of the desired shape. A disc of sheetmetal is held against the block by the lathe tailstock so as to rotate with the block when the lathe is turned on.

It is important that the surface of the former block be smooth to ensure a satisfactory finish for the item being spun.

A forming tool is used to exert appropriate pressure to the rotating disc causing it to stretch, bend and compress over the revolving block.

The forming tool is made from toughened steel and polished smooth where it contacts the work. It pivots at a locating pin in a rest attached to the lathe compound slide to allow the operator maximum flexibility when applying pressure to the spinning disc. See Figure 11.
ROLLING AND FORGING

Rolling and Forging are the oldest of the mechanical methods of shaping metals, forging dating back to the Bronze Age and rolling originating in 16th Century Europe. This primitive rolling was quickly followed by such developments as sheet mill operations in the 17th Century and bar and mass production work using a reversing mill in the 18th Century.

Although rolling is basically a hot working process, modern methods with finishing passes carried out cold have been developed. As with drawing the final stages of cold rolling provide a better surface finish as well as ensuring dimensional accuracy and a harder stronger and tougher final product.

Forging is invariably carried out when the metal is above its recrystallisation temperature and is therefore a hot working process.

4. ROLLING

This is the term used to describe the process which changes the cross-sectional shape of a piece of metal by passing the metal between suitably spaced and shaped rollers. The transportation of the metal billet between sets of rollers is by way of a table comprised of a number of freely revolving or live rollers, motor driven to give the billet direction.

The action of rolling causes micro-structural changes to the original cast billet or slab. The effects of weaknesses such as impurities, segregations, blowholes, cavities, piping and coring in castings are reduced by rolling. This, combined with the resulting smaller grain size, provides a more homogeneous product.

There are TWO general types of rolling mill.

(a) SHEET, STRIP AND PLATE MILLS.
(b) BAR, RAIL, JOIST ETC. MILLS.

(a) SHEET, STRIP AND PLATE: These comprise two smooth surfaced rolls rotating in opposite directions. The hot billet is fed into the rollers and reduced in thickness. The space between the rollers is adjustable to allow the production of various thicknesses of sheet, plate or strip.

Very often a series of roller sets in tandem form a line to enable the change from billet to sheet to be a single continuous operation. Figure 12 shows diagramatically a continuous hot rolling mill.

![Diagram of continuous hot rolling mill](image-url)

Fig. 12.
Rolling produces very little increase in the width of the billet. As the billet gets thinner its length increases dramatically.

Rolling is an efficient way of producing long lengths of material of uniform thickness from cast ingots or slabs from the slabbing mill.

If the finishing passes are carried out cold, annealing may be required between passes to eliminate the effects of work hardening.

(b) BAR, RAIL, JOIST ETC: The rollers for this type of mill have suitably shaped grooves cut into their surfaces to produce the required shaped bars, rods, rails, joists etc. The same general comments and information written in (a) (the sheet mill) apply to this type.

By using selected shaped rollers, items such as wire, R.S.J's, tube, corrugated sheeting, spheres and profile shaft shapes, can also be produced.

Any metal or alloy having a recrystallisation temperature above 150°C is suitable for hot rolling.

The evening out of the grain and fibre structure into axial directions gives strength and toughness properties which are not present in parts similarly shaped by machining.

5. FORGING

This is the term used to describe the metal forming process which uses heavy blows or pressure to form previously heated metal billets to the desired shape.

Forging is a hot working process which can be carried out by a blacksmith using hand tools and equipment or by machines using either hammers or presses.

TYPES OF FORGING:

(a) SMITH FORGING.

(b) DROP FORGING (CLOSED DIE).

(c) UPSET FORGING.

(a) SMITH FORGING: This is a hot working process where the operator (blacksmith) uses an array of specially shaped hand tools called fullers to concentrate sledge hammer blows at positions on the heated work.

The hot work piece or billet is supported using either the surfaces of an anvil or a second fuller inserted in a square hole in the anvil.

The skill of the blacksmith can quickly and accurately change a billet to the desired shape.

Such operations as drawing down, swaging, upsetting, cutting, punching and welding are carried out by the blacksmith.

(b) DROP FORGING: This is sometimes called closed die forging since the operation is carried out within the cavity of a closed die. It consists of squeezing a pre-heated billet, placed within the die, so that it takes the shape of the die cavity.

The required force can be provided by the impact of a hammer powered by steam or a hydraulically operated press.
This method is particularly valuable when large numbers of the one item are required. Spanners, connecting rods, gear blanks etc. are drop-forged to shape.

The metal die is dimensionally accurate so all the forgings will be identical.

Depending on the size of the part and the metal used, forces will vary from 100 KN to 500 MN.

For large work it may be necessary to use a series of dies and operations to achieve the final result.

(c) **UPSETTING**: This is the process used to increase the cross-sectional area of a billet at one or more positions along its length. The operation consists of a clamping device to hold the cold end of the billet and a moving die which strikes the hot end. A typical upsetting operation is the forming of heads for bolts, screws, rivets and pins.

As with the forming methods covered earlier in this Topic, the grain flow around the shape of the part produced by rolling and forging provides a strength and toughness not found in parts machined from bar stock.

Figure 13 shows the grain flow resulting from forging compared with the original grain direction in similar parts machined to shape.
<table>
<thead>
<tr>
<th>METAL</th>
<th>TEMP. RANGE °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel low - med Carbon</td>
<td>800 - 1300</td>
</tr>
<tr>
<td>Steel high Carbon</td>
<td>750 - 1100</td>
</tr>
<tr>
<td>Steel alloys (incl. Stainless)</td>
<td>950 - 1200</td>
</tr>
<tr>
<td>Copper</td>
<td>450 - 1000</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>600 - 800</td>
</tr>
<tr>
<td>Aluminium and alloys</td>
<td>325 - 475</td>
</tr>
<tr>
<td>Aluminium Bronze</td>
<td>800 - 900</td>
</tr>
</tbody>
</table>

It should be noted that the harder the alloy being forged the greater the wear on the dies particularly in drop-forging.