# Metals

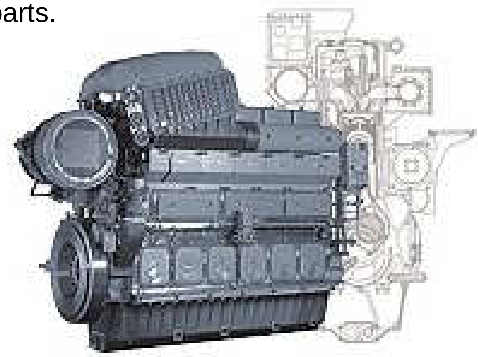


St Andrew's & St Bride's High School Technology Department

## Introduction

Metals are an extremely versatile design material and the huge variety of metals and their alloys can be used in many applications from jewellery to engine parts.

A small cast Paltinium and Gold Pendant



A 6m long ships diesel engine made from cast iron

Compared to all other materials, metals are stiff, strong and tough, but they are heavy. They have a relatively high melting point, allowing some metal alloys to be used at temperatures as high as $2200^{0}$C. Metals are ductile, allowing them to be shaped by rolling, forging, drawing, and extrusion; they are easy to machine with precision; and they can be joined in many ways. This allows a flexibility of design with metals that is only now being challenged by polymers (plastics).

The primary production of metal is energy intensive. Many, among them aluminium, magnesium, titanium, require at least 5 times more energy per unit volume than polymers (plastics). But metals can be recycled, and the energy required to do so is much less than that required for primary production. Metals can be either pure material extracted from ore deposits found buried in the earth's surface or made from a mixture of two or more metals combined with other elements. The latter are called ***alloys*****.**

## Material Characteristics Terms

Before considering different materials it is important that you have an understanding of the terms used to describe their characteristics:

**Strength** - the ability of a material to resist force and suffer no permanent deformation. A strong material requires high loads to **permanently** deform (or break) it - not to be confused with a stiff material, which requires a large load to elastically (non-permanent) deform it.

**Stiffness (Young's Modulus)** - the ability of a material to resist distortion when a load is applied. A stiff material requires a large load to **elastically** (non-permanently) deform it - not to be confused with a strong material, which requires a large load to permanently deform or break it.

**Plasticity -** the ability of a material to easily shaped and remain deformed when the load is removed.

**Ductility -** the ability of a material to be stretched and formed without fracturing. Copper, for example, is very ductile and behaves in a plastic manner when stretched.

**Brittleness -** the property of being easily cracked, snapped or broken. It is the opposite of ductility and therefore the material has little plasticity and will fail under loading without stretching or changing shape. Cast iron and glass are examples of a brittle material.

**Malleability** - the ability of a material to be shaped, worked or formed without fracturing. It is closely related to the property of plasticity.

**Toughness -** the ability of a material to absorb sudden loadings without permanent deformation or failure. Tough materials require high elasticity.

**Hardness** - the ability to resist erosion or surface wear. Hard materials are used in situations where two surfaces are moving across or over each other.

## Ferrous Metals

Pure iron is difficult to produce and not often used nowadays. Ferrous metals therefore tend to be alloys of iron and carbon. They tend to rust in moist conditions and are magnetic.

| Name | Properties | Uses |
|---|---|---|
| Cast Iron | Iron + 3.5% carbon. Brittle with a hard skin. Casts well. | Machine tools, vices. |
| Mild steel | Iron + up to 0.35% carbon. Malleable, ductile with a very uniform texture. | Nuts, bolts, screws, tubes, small non-cutting tools. |
| High carbon steel | Iron + up to 1.5% carbon. Malleable & ductile. Can be hardened and tempered. | Cutting tools, files, drills, saws, taps & dies, knives, scribers, lathe tools. |
| Stainless steel | Iron, carbon with Chromium, Nickel & Magnesium. Hard and tough. Corrosion and wear resistant. | Cutlery, sink units, dishes, teapots, boat fittings. |
| High speed steel | Medium carbon steel, tungsten, chromium & vanadium. Very hard. Excellent heat resistance. | Tool bits, drills, lathe cutting tools. |

### Steel Overview

Steels are the most important engineering materials, and cover a wide range of alloys based on iron and carbon. The strength of iron-carbon alloys, particularly after heat treatment, has been exploited for thousands of years (since the "Iron Age").

Alloy steels are mostly fairly cheap, covering a range of carbon contents (0.1-1.0%). The medium to high carbon content steels respond well to heat treatment (such as "quenching and tempering") to give very high strength and good toughness for gears, driveshafts, pressure vessels, tools.

All steels have a high density and a high stiffness. The strength and toughness of alloy steels can be varied enormously by alloying, working and heat treatment. Alloy carbon steels rust easily, and must be protected by painting or other coatings.

### Design Issues

High strength with good toughness, high stiffness, mostly very cheap, quite easy to shape, easy to weld, easy to recycle, high density, poor electrical and thermal conductivity

### Typical Products

Structures - oil rigs, railway track, bearings, gears, shafts, cutting tools, hand tools.

### Process Notes

Powder metal forming is most commonly used with high alloy steels. Rolling, extrusion and sheet forming are only used with low alloy (lower strength alloys). Machining gets more difficult for the stronger alloys (usually those with higher alloy content). Joining is suitable for use with most techniques. Friction welding can be difficult for high alloy steels.

### Environmental Issues

Steel production uses a lot of energy, but less than most metals. Steel is easily recycled - as it is usually magnetic it is easily sorted from mixed waste.

Detail of the steel structure in the Glasgow Science Centre Tower.

## Non-Ferrous Metals

These metals have no iron and therefore withstand moist conditions.  Non-ferrous metals are not magnetic.

| Name | Properties | Use |
|---|---|---|
| Aluminium | Pure metal from Bauxite ore. Strength to weight ratio good. Casts easily. | Window frames, food packaging, kitchen utensils. |
| Copper | Tough, ductile and malleable. Good conductor.  Expensive. | Central heating pipes, electric wires and cables, jewellery. |
| Tin | Heavy and soft material with a low melting point. | Surface coating on sheet steel. |
| Lead | Very heavy, soft, weak, ductile and malleable.  Low melting point and can be cast. | Roof flashing, plumbing, solder. |
| Zinc | Weak and difficult to work.  Used extensively in alloys. | Surface coating on steel (galvanized).  Dustbins, corrugated sheets, castings. |

### Aluminium Overview

Aluminium is a lightweight, reasonably cheap metal widely used for packaging and transport.  It has only been widely available and used for the last 60 years.  Raw aluminium has low strength and high ductility (ideal for foil).  Strength is increased by alloying, e.g. with silicon, magnesium, copper, zinc and heat treatment.  Some alloys are cast; others are used for wrought products.   Aluminium is quite reactive, but protects itself very effectively with a thin oxide layer. The surface can be "anodised", to resist corrosion and to give decorative effects.

### Design Issues

Aluminium Alloys have a high strength-to-weight ratio, high stiffness-to-weight ratio, high electrical and thermal conductivity, easy to shape, easy to recycle, difficult to arc weld.

### Typical Products

Aircraft, bicycles, car engines, "Space frame" car bodies, drinks cans, window frames.

### Process Notes

Metal forming - easy to use with most metal forming processes.  Very suitable for rolling at all thicknesses down to foil.  Die casting is the most commonly used casting process.   Usually comparatively soft, so readily extruded.  Sheet forming is important use for cans.  Machining - relatively soft, so readily machined. Joining - suitable for use with most techniques, although difficult to arc-weld and an inert gas is needed.

### Environmental Issues

Aluminium production uses lots of energy (4% of total US energy consumption!).  Aluminium is easily recycled - this only uses 1% of the energy needed to produce the metal.  Aluminium use in cars is growing rapidly - low weight means good fuel economy and low emissions metal

The aluminium space frame chassis for Audi's new A8 luxury car.

## Alloys

An alloy is a mixture of two or more metals formed together with other elements such as copper and zinc to create new materials. These new materials tend to have more desirable qualities than pure metals.

| Name | Composition | Properties | Uses |
|---|---|---|---|
| Stainless steel | Iron & carbon<br>+ Chromium<br>+ Nickel<br>+ Magnesium | Ferrous. Hard and tough. Corrosion and wear resistant. | Cutlery, sink units, dishes, teapots, boat fittings. |
| High speed steel | Medium carbon steel<br>+ tungsten<br>+ chromium<br>+ vanadium. | Ferrous. Very hard. Excellent heat resistance. | Tool bits, drills, lathe cutting tools. |
| Brass | Copper<br>+ zinc | Non-ferrous. Corrosion resistant, hard. Casts well, work hardens. Easily joined, polishes well, good conductor. | Taps, decorative items, boat fittings, casting. |
| Bronze | Copper<br>+ Tin<br>+ zinc | Non-ferrous. Strong and tough. Wear and corrosion resistant. | Statues, water fittings, coins. |
| Duralumin | Aluminium<br>+ manganese<br>+ magnesium | Non-ferrous. Very good strength to weight ratio. Age hardens. Machines and finishes well. | Aircraft parts. |

**Brass Overview**
Brass is quite an expensive alloy of copper and zinc. Alloying, working and heat treatment gives it a much better strength than copper and a good corrosion resistance.

**Design Issues**
Reasonable strength, corrosion resistant, easy to shape, quite expensive

**Typical Products**
Ornamental fittings, plumbing fittings, screws

**Process Notes**
Metal forming - readily extruded because it is quite soft. Rarely rolled, forged or used in sheet forming. Not used much with powder metallurgy as it tends to oxidise. Machining - Readily machined. Joining - Soldering and brazing are important for electrical connection and pipe. Adhesive bonding rarely used.

**Environmental Issues**
Copper and brass production uses quite a lot of energy. Brass is easy to recycle, but the volume in use is small.

# *Metal: Summary Table*

| Metal name | Family | | Manufacturing Process | | | | | | | | | | | | | Cost (relative) | Supply | General Information |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ferrous (with iron) | Non-ferrous | Rotational Casting | Die casting | Sand casting | Pressing | Piercing & blanking | Forging | Extrusion | Turning | Milling | Arc welding | Spot Welding | Riveting | Adhesives | | | |
| Mild Steel | √ | | √ | | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | € | rod, sheet, bar, tube | Perhaps the most common metal it is used in general structural work, girders, nuts, bolts, screws, non cutting tools and car bodies. |
| High Carbon Steel | √ | | | | | | | √ | √ | √ | | √ | | | √ | € € | rod, bar | Harden and tempered and used in hand tools as the cutting edge is lost at high temperatures. |
| Stainless Steel | √ | | √ | | √ | √ | √ | √ | √ | √ | √ | √ | | √ | √ | € € € | rod, sheet, bar, tube | Stainless steel has a high tensile strength and resists abrasion and corrosion because of its high chromium content. It is difficult to cut or file and is used is sinks, kitchenware, pipes and aircraft. |
| High speed Steel | √ | | | | | | | | √ | | | | | | √ | € € € € | rod, bar | High Speed Steel is hardened and tempered and is used in cutting tools for lathes, milling cutters and drill bits where it will retain hardness up to temperatures of 600℃. |
| Cast iron | √ | | √ | | √ | | | | | | √ | √ | | | √ | € € | Ingot | Cast Iron has a hard skin but soft core and is strong in compression. Used in engine parts, vices, manhole covers and machine tools. |
| Brass | | √ | √ | | √ | √ | √ | √ | √ | √ | √ | | | √ | √ | € € € € | rod, sheet, bar, tube | An alloy of copper and zinc which is used in castings, boat fittings, ornaments, wood screws, door handles and hinges. |
| Bronze | | √ | √ | | √ | | | | | √ | √ | | | | √ | € € € € | ingot | Bronze is an alloy of copper, tin, zinc, phosphorus and it is harder than brass. Used in bearings, gears, statues, coins. |
| Aluminium | | √ | √ | √ | √ | √ | √ | | √ | √ | √ | √ | | √ | √ | € € € | Ingot, bar, tube sheet, | Aluminium is rarely used as a pure metal and it is usually alloyed with copper to improve strength (duralumin) |
| Duralumin | | √ | √ | √ | √ | √ | √ | | √ | √ | √ | | | √ | √ | € € € € | rod, sheet, bar | The most common aluminium alloy used in car bodies, cookware, aircraft, boats, engines, window frames and drink cans. |
| Copper | | √ | √ | | √ | √ | √ | | √ | √ | | √ | | √ | √ | € € € € | sheet, wire, tube | It is malleable, ductile and conducts electricity. Copper roofs become tarnished in the air resulting in a green finish known as verdigris. Used in wire, water pipe, boxes, bowls and rivets. |
| Tin | | √ | √ | | √ | | | | | | | | | | √ | € € € € € | Ingot, rod, | Tin is very soft and is used in soft solder and pewter or to cover sheet steel (tinplate) to prevent rusting. |
| Lead | | √ | √ | | √ | | | | | | | | | | √ | € € € € | Ingot, sheet | Lead is a soft but poisonous metal used in roof flashing, car batteries or to form alloys. |
| Zinc | | √ | √ | √ | √ | | | | | | | | | | √ | € € € | Ingot, sheet | A brittle metal with a low melting point used in dies casting and galvanise steel to prevent rusting |

# Metal Processes

**Introduction**

The choice of which manufacturing process is most suitable depends upon; material, shape, size, degree of accuracy, surface finish, unit cost and most critically the number of components to be made – the batch size.

Manufacturing processes can be grouped into a number of broad families:

**Material Preparation** (converting raw materials into standard stock sizes):

- Extrusion (metal & polymer)
- Rolling (metal)
- Spindle moulding (wood)

**Material Processing** (giving the component its final form):

- Injection moulding (polymer)
- Rotational moulding (polymer)
- Blow moulding (polymer)
- Compression moulding (polymer)
- Vacuum forming (polymer)
- Sand casting (metal)
- Die casting (metal)
- Drop forging (metal)
- Forging (metal)
- Pressing (metal)
- Stamping (metal)
- Piercing (metal)
- Blanking (metal)
- Turning (wood, metal & polymer)
- Milling (metal & polymer)
- Routing (wood)
- Laminating (timber & polymer)

**Assembly Processes** (bring together the component to complete the product):

- Adhesive (wood, metal & polymer)
- Arc welding (metal)
- Spot welding (metal)
- Heat welding (polymers)
- Riveting (metal & polymer)
- Mechanical Fastenings (wood, metal & polymer)

**Finishing Processes** (enhancing and protecting the product's component parts):

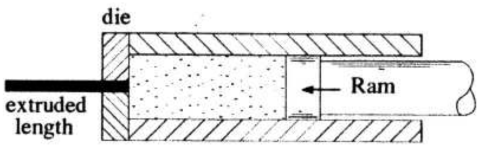
- Varnish (wood)
- Lacquering (metal)
- Powder coating (metal)
- Aqua Transfer printing (metal & polymer)
- Painting (wood & metal)
- Galvanizing (metal)
- Anodising (metal)

## Metal Preparation - Extrusion

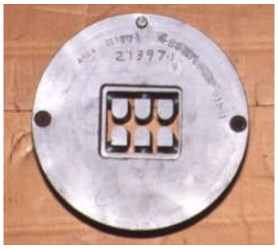
A selection of just some of the possible extrusion shapes

The extrusion of metal is used to produce long straight lengths of material with a uniform cross-sectional shape. The cross-sections possible include solid round, L and T shapes, tube or complicated irregular hollow shapes.

Extrusion can be likened to squeezing tooth paste out of a tube – long lengths of material are formed in the same cross sectional shape as the tube opening. Common metals that are extruded include aluminium, copper, magnesium, steel, and stainless steel.




Extrusion involves squeezing a hot metal billet inside a closed cavity with a shaped opening formed by a die using either a mechanical or hydraulic press.



Dies showing the detailing possible when extruding lengths of metal

Extrusion often minimises the need for secondary machining, but it does not give the same dimensional accuracy or surface finish as a machined part. However, this process can produce a wide variety of cross-sections that are hard to produce cost-effectively using other methods. Minimum thickness of steel is about 3 mm, whereas with aluminium and magnesium this can be extruded to about 1mm.

Cold extrusion can be used for most materials -subject to the design of robust enough tooling that can withstand the stresses. Examples of the metals that can be extruded are lead, tin, aluminium alloys, copper, titanium, vanadium and steels. Examples of parts that are cold extruded include collapsible tubes, aluminium cans, cylinders, gear blanks. The advantages of cold extrusion include, no oxidation, good mechanical properties due to the cold working, and a good surface finish.

### Materials & Shapes

Mainly used with the softer metals, e.g. aluminium, copper, zinc. In general, the softer the metal, the more intricate the shapes that can be made. Useful for long thin parts with a constant cross-section. Possible cross-sections are usually limited to less than 100mm across. Dimensional tolerance and surface finish may be poor with hot extrusion. Cold extrusion is possible for some metals giving better properties.

### Economics

Although extrusion appears to be a continuous process, it is really a batch process as it needs to be interrupted to load new billets. Typical machine prices are in excess of £50,000. Dies can cost upwards of £1,000 to make (depending on size), but a lot more to design well. More frequent die replacement is needed for higher strength metals. Production rates from 5-10 metres/minute are possible. Usually only economical for a batch size of 1,000 – 1,000,000 metres.

### Typical Products

Metals such as aluminium, copper, magnesium, steel, and stainless steel are extruded to form window frames, tubing, building and car trim, aircraft parts, railings & wires. Extrusion can be used to form 1 – 1,000kg lengths to an accuracy of 0.2 - 2mm.

## Material Preparation: Rolling


A selection of rolled steel components

Rolling is an alternative to metal extrusion and it is used to produce long lengths of straight material with a uniform external cross-section. Rolling cannot, however, be used to form hollow components.

Rolling is a very common process and is used to form 90% of all stock sized steel by squeezing the metal ingot between two massive rolls or dies.

In hot rolling the metal ingot is heated to around 2/3 of its meting point and forced through a series of roller dies that progressively form the profile. This produces components with particularly good mechanical properties because the metal grain reforms to the rolled profile as the material cools. This leaves hot rolled material relatively soft with a surface layer of oxide (called black bar in the case of hot rolled mild steel).

Cold rolling produces good dimensional accuracy, an oxide free surface finish and a work hardened surface making the metal strong. Often hot rolling is first used to shape the metal and cold rolling (or drawing) is then used to finish the material and work hardens the surface.


A selection of cold rolled steel components with a good surface finish and dimensional accuracy.

### Materials & Shape

A hot ingot in moved back and forth through a set of connected die rolls. Each roll gets closer the final shape; the last pass will finish the rolled shape. Rolling can be used to make thick sections such as slabs or large I-beams. In practice, there do not need to be many separate 'dies' if the operator can move the rolls closer together between passes.

### Economics

For making stock items, rolling has few competitors. For this reason, it is usually performed by the foundries before passing on to customers for further processing. For long shaped sections, rolling is the only viable option for larger cross sections - for smaller cross section extrusion may be more economic. Machines can cost millions of pounds. Typical economic batch sizes 10,000 – 1,000,000

### Typical Products

*Metal I-beams, rails, sheets, plates, foil with a low shape complexity. Typical weight range 0.1 – 100kg with the minimum thickness of 0.2mm.*

Rolling machine set up to produce rectangular bar or sheet.

## Sand Casting

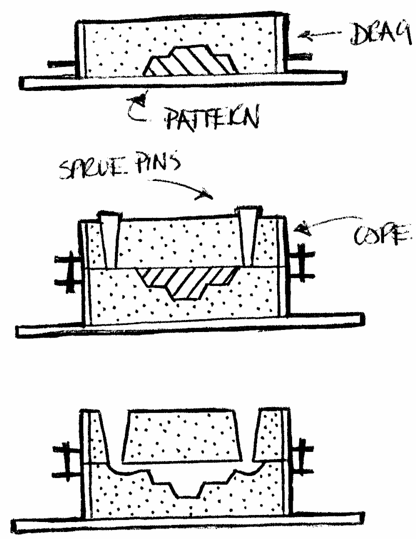
Sand casting involves pouring molten metal (aluminium, cast iron, brass) into a shaped impression, called a mould, made in sand.

A selection of sand cast metal components. They all feature rounded corners (fillets), stiffening webs and tapering sides.

A turbine mould being prepared in before casting.

This features a sand core used to produce hollow shapes within the metal casting.

The mould is made inside a two-part box, called a cope and drag, by packing sand around a shaped pattern. The pattern can be made from expanded polystyrene (investment casting), modelling clay, or more commonly painted hardwood. The sides of the pattern must be tapered (draft) to allow it to be removed from the sand and all corners must be rounded (filleted) to prevent stress lines forming in the metal as it cools.




The pattern is placed in the drag and fine sand is sieved and packed around. The drag is then turned over and the cope attached. Sprue pins are inserted and the sand is packed around. The pattern and sprue pins are removed leaving the mould cavity. The box is then reassembled and ready to receive the molten metal.

The molten metal is poured in through one of the sprue pin holes (runner) and as the mould fills up the gases escape via the second hole (riser). When cooled the cast object can be broken out of the sand mould.

The patterns used for sand casting are relatively cheap and easy to produce but the surface texture of the cast component tends to be poor and may require further machining or finishing. Casting does allow complex shapes to be manufactured that could not be produced in any other way.

### Materials & Shape

Most metals can be cast but this process is most commonly used to form products out of aluminium, bronze, brass or cast iron. There is almost no limit to the size of a sand casting - casings over 5m wide are routinely made (e.g. ship propellers). Most shapes can be made, but the surface often has a characteristic rough finish which may need machining. Removing the extra material left from risers/gates can also greatly add to the cost of the finished product.

### Economics

The basic equipment cost is low - from £500 to £3,000, however, automation and higher temperature furnaces can increase this price considerably. The limit on the production rate depends on the metals cooling time. Small parts can be produced at several per hour - large parts can take hours or even days to fully cool. The labour intensive nature of the process mean it is usually only economic for small batches but with automation the volume can be viable between 1 – 100,000 units.

### Typical Products

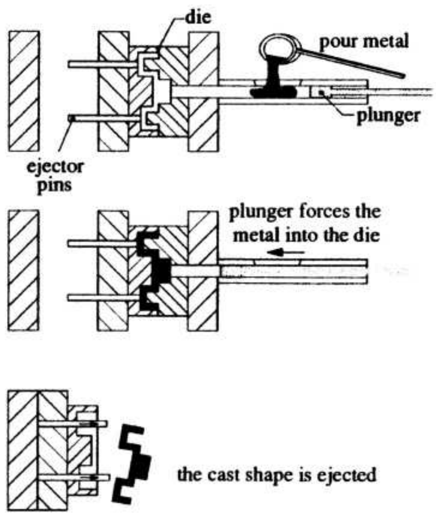
Aluminium, cast iron, brass, bronze item including engine parts, plumbing fittings, pump housings, machine tool bases, ship propellers and decorative items. The weight of product can vary from 0.3kg to 1,000kg and the minimum thickness of 5-100mm.

## Die Casting

Die-casting is a highly automated process used in the mass production of aluminium, magnesium or zinc alloy components where a high degree of accuracy and excellent surface finish is required. Die-casting is used to produce items such as toy cars, military models, pencil sharpeners, car parts and camera bodies.

Die cast zinc engineering components.

The molten metal is forced into the shaped water-cooled die mould where it rapidly solidifies and is then ejected. Very little finishing is required other than removal of the sprue gate and any flashes caused by leakage of material where the dies meet.




### Materials & Shape

Die casting is mostly used for low melting point alloys such as aluminium, zinc and magnesium. In general only small parts are made, but it can be used for components up to 20kg. Complex parts can be made with good dimensional accuracy and surface detail. A draft (taper) angle has to be incorporated to alloy easy ejection of the part. Parts are left with good mechanical surface properties. Ejector pin marks are often visible.

### Economics

Die casting equipment is expensive, and can cost well over £100,000 while the dies cost many thousand pounds. Dies require replacing after a few hundred thousand uses and this can take several weeks to manufacture, mean prototype testing is slow. The production rate depends on how long the part takes to cool before it can be ejected. This can give rates of 500+ parts per hour in normal conditions. Because of the high capital cost, the process is typically used for batches of 100,000+, although it may be economical for volumes between 5,000 –1,000,000 units.

### Typical Products

Aluminium, zinc or magnesium alloy small toys e.g. cars/soldiers, hand tools, disc drive chassis, motor casings, carburettors. The weight of product can vary from 0.05kg to 20kg with a medium to high shape complexity and an accuracy of 0.15-0.5mm.

A robotic arm used in an automated factory to remove components after die casting.

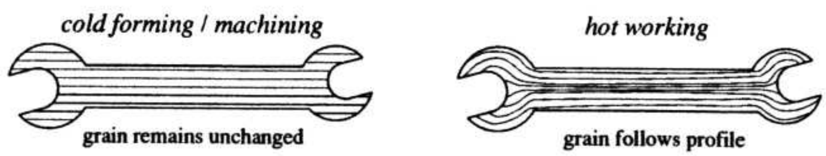
## Forging

The forging involves heating metal, to 60% of its melting temperature, and then hammering into the required shape. Forging is a skilled and labour intensive process that is only really suitable for one-off or low volume batch production.


A selection of hand forged steel components

Just about any metal can be forged, some of the most common include: carbon, alloy and stainless steels; very hard tool steels; aluminium; titanium; brass and copper; temperature alloys which contain cobalt, nickel or molybdenum.

Hot forging refines the grain structure and improves physical properties (such as strength, ductility and toughness) of the metal. The forging process can create parts that are stronger than those manufactured by any other metalworking process. This is why forgings are almost always used where reliability and human safety are critical. But you rarely see forgings, as they are normally component parts contained inside airplanes, automobiles, tractors, ships, oil drilling equipment and engines.




**Materials & Shape**
Any metal can be forged. The forged component is left with mechanical properties however an oxide layer forms on the surface and this usually requires further processing before finishing. One-off or very low volume batches can be forged manually by a skilled blacksmith using a hammer and anvil but for larger batches powered hammers and jigs may be used to speed up production and ensure uniformity in the component.

**Economics**
Production rate is limited by the insertion and removal of the blank, so some form of automation is often used. As a result, machines can cost £100,000+, but can produce many parts a minute (if small). As both the machines and the dedicated dies are costly, production runs in excess of 50,000 are often needed to produce small parts economically. Large parts can be produced economically at smaller batch sizes, because there is less competition.

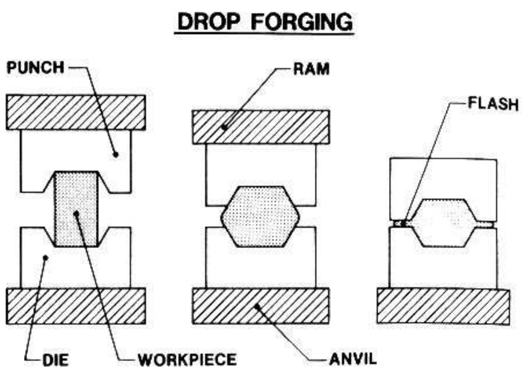
**Typical Products**
Metal wrought iron work including fences, gates and decorative furniture, high stressed mechanical parts such as aircraft components, chains and hand tools.

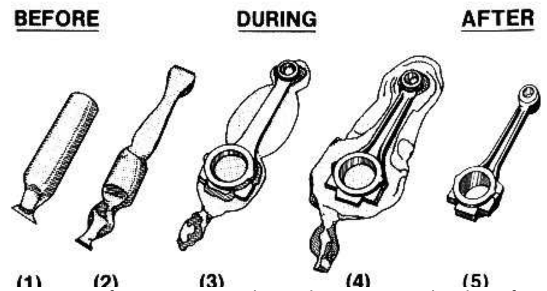

Power hammers being used to forge steel engine components.

## Drop Forging

Drop forging of metal is the volume production version of hand forging. The process involves repeatedly stamping the hot metal between a punch and die using a hydraulically power hammer until the component shape as been formed.

A selection dropped forged steel components.




The stages in forming a typical metal component by drop forging.

### Materials & Shapes

Any metal can be forged, provided it is hot enough (60% of the melting temperature). Typical sizes for closed dies range from 10g to 10kg, depending on complexity. The part is left with good surface and mechanical properties, although cold-forging can perform even better. Complex parts can be formed using a series of forging dies with increasing levels of detail. A draft (taper) angle has to be incorporated to allow easy removal of the part. Drop forging leaves a parting line and flash (waste metal squeezed out between the die halves) on the component. The flash waste has to be removed to finish the component although this metal is recycled.

### Economics

Production rate is limited by the insertion and removal of the blank, so some form of automation is often used. As a result, machines can cost £100,000+, but can produce many parts a minute (if small). As both the machines and the dedicated dies are costly, production runs in excess of 50,000 are often needed to produce small parts economically. Large parts can be produced economically at smaller batch sizes, because there is less competition.

### Typical Products

Metal spanners, pedal cranks, gear blanks, valve bodies, engine components with a typical economic batch size of 10,000 – 1,000,000 units.

Hand finishing the flashing on a drop forged crank shaft for the diesel engine

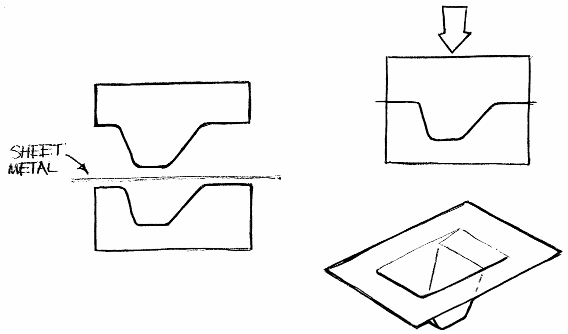
Drop forging used to form a steel axle for a railway carriage.

## Press Work: Press-Forming

Presswork is the generic term applied to the cold working of sheet metal with shaped presses. Pressworking is among the most important metalworking processes. It is used in the manufacture a wide range of sheet metal products using processes such as blanking, piercing, drawing, stamping, pressing, spinning and bending.


A selection of just some of the sheet metal product made by press forming.

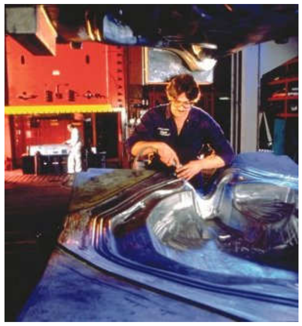
Press-forming is used to produce 3D products from thin sheet metal. Examples of such items are kettles, baking tins, tubular furniture, car bodies and aircraft frames.




The dies used in press forming are expensive to produce and have to be able to with stand the many hundreds of tonnes loading exerted by the hydraulic press. The die press is made of two parts that allow for the thickness of the metal. Components start out as flat sheets, which are then blanked out, to the required shape. The large force is then used to press the blank into the required form.


A press-forming machine used to produce simple bends on sheet metal used on building cladding.

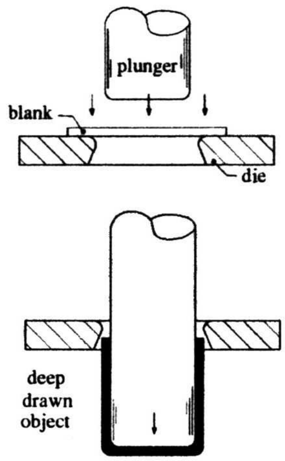
A complex 3D shape press-formed in stainless steel.



## Press Work: Drawing

The process of drawing is the main process in the production of three-dimensional curved pressings e.g. drinks cans, gas cylinders, and bullet casings.

The sheet material (blank) is placed on a shaped die, which has a highly finished surface and lubricated to minimise friction. A punch is then forced into the material, drawing it down to form the object. The depth, which can be drawn in one punch, depends on the type of material, its tensile strength and the tool design.





The stages of drawing a drinks can.

## Press Work: Piercing & Blanking

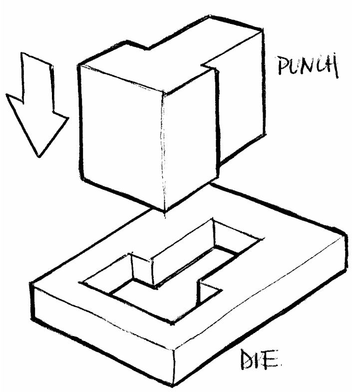
Blanking is the process of stamping out the external shape in sheet metal.

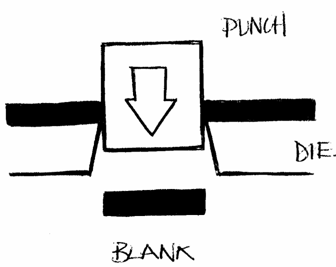
A simple steel spanner for use with flat-packed furniture is produced by blanking

Piercing involves punching internal shaped hole(s) in the sheet metal blank.

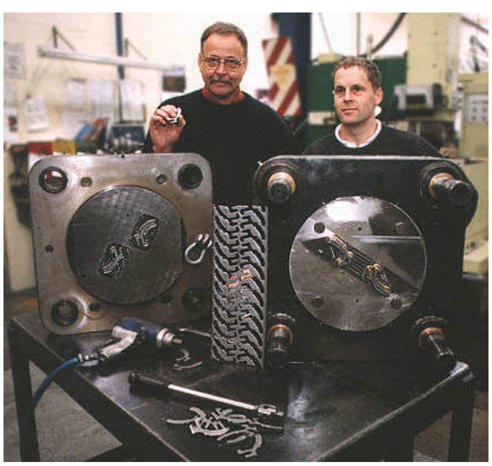
A bicycle sprocket is made in one operation by blanking (outer shape) and piercing (internal detailing)

These two presswork processes are usually carried out at the same time when a large number of identical items are required. These processes are similar and work by passing a length of sheet metal from a coil or roll between a hardened steel punch and matching die. The punch is forced through the strip and shears the metal on the die. The shape is formed immediately in one press. This process is automated by passing the metal strip through by the exact amount on every stroke. Bicycle chains and jewellery chain links are examples of products made in this way.




*A high speed blanking & piercing pressed use in high volume batch production of sheet metal products*



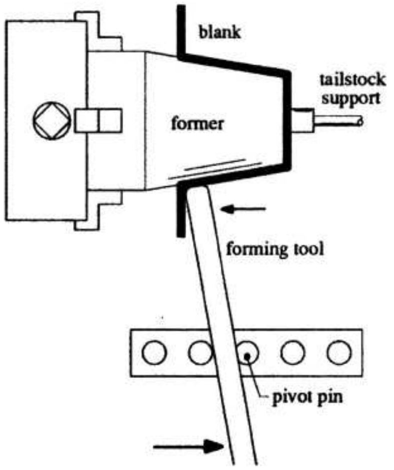
*The die and punch, waste material and the blanked sheet steel component*

## Press Work: Spinning

Spinning is a simple process used to form symmetrical hollow objects such as bowls or vases out of sheet metal.

The metal blank is pushed against a rotating wooden former using the lathe tailstock. A forming tool is used like a lever to wrap the metal blank against the former. The uneven edge is then machined off.

A selection of the sheet metal products that are manufactured by spinning.




A sheet metal lampshade being formed by spinning

### Materials & Shape

Mild steel less than 6 mm thick is the most common press formed material. Blanking (shearing) is used to cut parts for subsequent processing, sheet is shaped with bending (1-D) and drawing (2-D), pressing contains elements of all three. Surface finish is usually good, but this is dependent on good quality die design. A wide variety of shapes can be made, but die design must account for the elastic 'springback' of the sheet after forming. Some scrap is always produced and cannot be directly recycled.

### Economics

Primarily used when near-net-shape (finished form) processes are impractical in terms of time or materials e.g. for car body panels. Simple manual equipment can cost only a few thousand pounds, but is only used for prototyping and small batches as the production rates are low. Automated tooling (which can be expensive) is usually dedicated to individual components, so is normally only used for long production runs in order to be cost-effective. Economic batch size 25,000-250,000 with automated production rate being very high (drinks cans can be produced at almost a 1,000 a minute).

### Typical products

Sheet metal from 0.2-6mm thick in products such as cans, washing machine cases, car body panels, kitchen utensils, hubcaps, metal desks etc.

Mild steel car body panels: blanked, pierced and press formed ready to be spot welded together

## Metal Turning

Metal turning lathe is used to form cylindrical or conical shapes in metal and some types of plastic. The material is held firmly in a rotating chuck while a shaped cutting tool removes the waste using a simple wedging action. A variety of processes can be carried out on the lathe for example turning cylinders, creating texture (knurling), accurate drilling and threading.

When mass-producing a component the turning process is automated. This machining is carried out automatically using a CNC (Computer Numerically Controlled) lathe which converts a CAD (Computer Aided Drawing) file into a set of control instructions for the cutting tool. This helps to ensure accuracy, reduce the lead-time between the design and manufacture, allows small batch production to be automated and increases productivity by machining the items quickly again and again.


A selection of the components machined on a metal turning lathe.

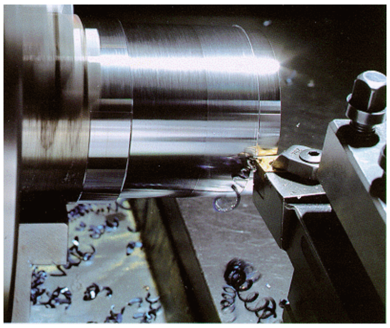

A CNC metal lathe used to automatically produce components. Note the ejector chute to remove the machined components.

### Materials & Shapes
**M**ost metals and certain polymers can be turned into circular and cylindrical forms. Turning produces a good quality surface. The turning process involves the removal of material to form the component and hence this process produces waste which is difficult to recycle.

### Economics
**T**urning is primarily used to produce finished components rather than products. Manual turning is used for one-off or small batch production while a CNC machines are used for larger volumes. Basic manual lathes can cost less than £1,000 while CNC equipment £10,000+.

### Typical Products
Metal products such as engineering components, bolts, piston rods, shafts etc.

A cast aluminium alloy piston with the end machined on a CNC metal lathe before fitting in the motorcycle engine.



A CNC metal lathe machining a steel billet into a component.

## Milling

Milling is a machining process used to remove waste metal or polymer in order to produce 3D forms out of solid block.The material is securely clamped to the machine table and then the whole assembly is fed across a rotating multi toothed cutter to shape the component.  The machines used industrially can be extremely sophisticated - the cutting head is often able to twist and turn in many directions!

A selection of milled metal components showing the level of detailing possible.

A boat's propeller being milled out of solid brass as an alternative to casting.

A manual milling machine used for one-off or low volume batch production.

When mass-producing a component the milling process is automated.  This machining is carried out automatically using a CNC (Computer Numerically Controlled) mill which converts a CAD (Computer Aided Drawing) file into a set of control instructions for the cutting tool.  This helps to ensure accuracy, reduce the lead-time between the design and manufacture, allows small batch production to be automated and increases productivity by machining the items quickly again and again.

**Materials & Shapes**

Almost any material can be milled, although difficulties arise with very brittle materials (e.g. ceramics) and very hard materials (e.g. tool steel).  Milling is used in metals primarily to shape parts by cutting edges, slots or grooves.  It is often used to complete parts that have been formed by a near-net-shape process (e.g. casting or forging).  Milling is unusual for wooden products, although variants such as routing can be used to form grooves and mouldings.

**Economics**

Milling machines vary in price from £1,000 to £1,000,000.  Milling is generally a very slow way to produce a component - but it can be economic for prototyping or small batches. High speed machining centres are used where the accuracy of milling is required to finish a component. The cost of milling on a commercial scale is often a balance between higher speed and longer tool-life.

**Typical Products**

Metal or polymer components formed from a solid billet of the material or used to finish casting (e.g. top of engine block).


A CNC milling machine which uses the CAD drawing to generate the control program for the movement of the cutting tools.

Titanium golf putter machined on a CNC mill.

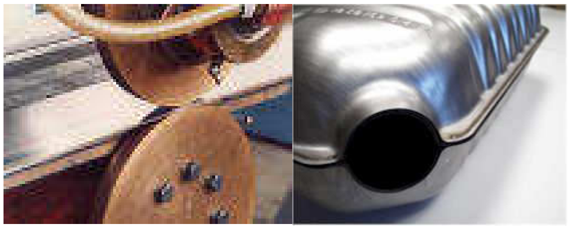
## Welding

Welding is a permanent way of joining metal components and this technique is used with 70% of the all the steel produced in the UK. Welding applications range from largest structures to the micro joining of electronic circuits.

Manual Arc welding of steel.

There are several types of arc welding - MMA (Manual Metal Arc) is probably the most well known. Automated arc processes include TIG (Tungsten Inert Gas) and MIG (Metal Inert Gas). All arc processes use a filler to join the two pieces - in MMA and MIG the filler also serves as the electrode which makes the electric arc. In manual arc welding, a welding rod is struck over the surface of the metal and then just lifted off. The electrical current jumps across the gap and carries the molten steel from the rod to form the weld. At the same time the flux covering on the welding rod forms a protective skin over the weld which can be chipped off when the weld cools. Safety precautions must be taken to protect the welder from the bright arc and the noxious fumes. Good welding requires a lot of skill, and in industry a welder must have special qualifications.
There are other more specialist arc welding processes such as spot welding or seam welding which are used on sheet steel and work without a filler. They rely on the electrical current melting the two surfaces together and forming the weld

Manual and automated spot welder used on sheet steel products such as car body panels.



Seam welding where two round copper electrodes roll along the edge forming the weld. This technique is limited to products where the electrodes can follow the outside profile such as in the sheet steel fuel tank for a car.

### Materials & Shapes

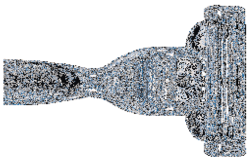
Although many metals can be joined with MMA, it is most commonly used for steel. Other materials, such as aluminium, are usually joined by more sophisticated arc welding processes (e.g. MIG, TIG). MMA is portable and so suitable for repair or on-site work. Thin plates may require only one pass for a successful join. For thicker plates, multiple passes may be required to fill the gap. For thin plates, the edges may be square. For greater thicknesses, the edges need to be bevelled to allow the gap to be filled more easily. In the area that has been affected by heat, the properties of the material may change greatly.

### Economics

The cost of MMA equipment can be less than £100. However, the production rate is slow so it is only economic for one-off jobs, repair work and difficult access situations.

### Typical Products

Metal components such as car bodies, ships, oil rigs, pipelines, pressure vessels.



Laser spot welding is used to join the 3 stainless steel razor blades with 13 welds in a cycle time of 1 second.

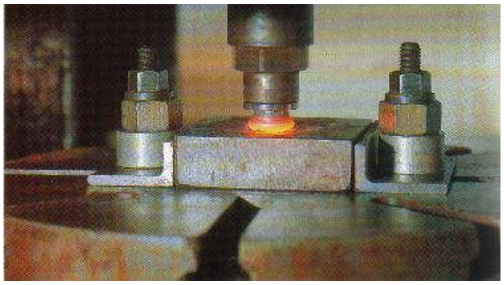
Titanium bike frame TIG welded together

## Friction Welding

### Materials & Shapes
Usually, at least one of the parts to be joined must be circular - this can be solid or hollow. One of the materials to be joined must soften before melting. Used to join different materials to each other (e.g. polymers to metals).

### Economics
Basic equipment costs around £10,000, but automation can increase this significantly. Most suited economically to joining pipes and attaching studs. For similar metals, competitive with arc welding for the geometries it can do. But because of the capital cost, it is not competitive where only a small number of joints are required.

### Typical Products
Thermoplastic and metal components such as pipes, two-part bumper, fuel tanks, fuel pumps, expansion vessels, instrument panels, air channels, parcel shelves, inner door panels, spectacle frames, motor saw housings, heating valves etc.



Friction welding a steel stud onto a plate by placing it in a drill and rotating at high speed.

## Riveting

Riveting is an old established technique which is used to permanently join materials together. Traditionally riveting was solely a manual technique where a hole is drilled through the materials, the rivet is inserted and then hammered until it expanded and joined the pieces together. On large engineering projects such as shipbuilding and civil engineering, the steel rivets were heated to red hot and then formed with a pneumatic or hydraulic hammer (this has been replaced by welding or bolting). Today riveting usually involves pop or self-piercing riveting.

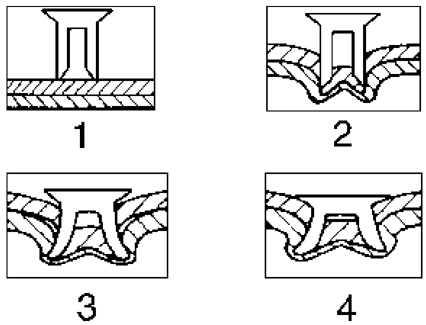
A hot steel rivet being formed by a pneumatic hammer.

Pop riveting is used to join thin pieces of metal or polymer. The pop rivet has two parts; the pin and the rivet. The pop rivet pliers are used to pull the pin through the rivet and as this happens the rivet is deformed so that it joins the pieces together. This process is used on thin metal or plastic where the joint does not have to be very strong and it is ideal for situations were access can only be gained from one side such as in heating and ventilation ducting and air frame construction. Pop riveting is a relatively slow technique which does not lend itself to large batch production due to the need to pre-drill holes before forming the rivet.

Pop rivets and an air operated pop rivet gun used to join sheet aluminium to an aircraft wing.

## Self-Piercing Riveting

Self-piercing riveting is a one-step joining technique suitable for ductile metal and polymers up to a maximum thickness of 10mm. As it relies on a mechanical interlock to form the permanent join and it can be used on materials and combinations of materials where, for instance, spot welding is difficult or even impossible. Self-piercing riveting involves driving a pipe shaped steel rivet with plane solid head into the two layers of the materials using a pneumatic gun. The rivet makes its own hole and joins the parts together in one moment.




### Materials & Shapes

Self-piercing riveting is a simple; one-step joining technique that relies on the mechanical interlock to join sheet materials together up to a maximum of 10mm in total thickness. The nature of the process means that only ductile non-brittle sheets can be joined using this technique. The pipe shaped steel rivet is forced through the surface of the two materials joining them together. It offers a good fatigue performance, often better than spot welds and can be used for many different combinations of materials. Joining of more than two sheets is possible.

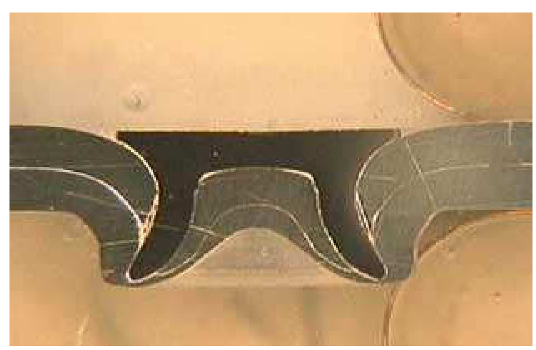
### Economics

It is a fast process which can readily be automated for large batch production. Unlike welding there are no fumes or heat produced and little noise emission. There is little or no damage caused to pre-finished materials and the tooling has a long life (20,000 joints are possible without maintenance).

### Typical Products

Ductile sheet metal and polymer components such as automotive, heating, ventilation and building industries, for pre-painted steels for white goods, and for joining aluminium used for road signs.

A robotic arm with a self-piercing riveter used for high volume production.



A cut through a self-piercing rivet showing clearly how it joins the sheets together.

## Mechanical Fastenings

Bolts, screws and patent fixings are a semi-permanent way to assemble a range of different material components. These are bought 'off-the-shelf' from specialised manufactures and come in a variety of different forms. They allow products to be assembled on a semi-permanent basis using simple tools like a screwdriver or spanner. Some form of mechanical joining needs to be used where products need to dismantled during their normal life, e.g. where repair or maintenance is likely. With the move towards efficient recycling, there is likely to be increased use of mechanical fastening.

A selection of just some mechanical fastenings available.

### Materials & Shapes

Virtually any material in any shape can be joined by mechanical fastening - given enough ingenuity! Practical limitations come from being able to form holes - this limits the options for ceramics and composites. Snap-fit joints are especially suitable for low stiffness materials like polymers, especially good for joining different materials (e.g. composite to metal). Joint quality is reliable and readily determined, given sufficient operator skill. However, mechanical joining usually reduces fatigue life. Essential where two parts will move relative to each other (e.g. hinges for doors). The non-permanence of many fasteners is useful for products that may need repair/maintenance or need access to the interior.

### Economics

Economic for any batch size from one-offs to mass production (with or without automation). Ease of mechanical joining (especially with snap fits) means low skilled workers can be used. For fasteners, there can be a significant stock cost in ordering and keeping track of so many components! By far the dominant means of joining parts. Competes with welding for thick metallic sections where a permanent joint is needed. Competes with adhesives for polymers and woods where a permanent joint is needed.

A nut and bolts allows semi-permanent joining of a wide range of materials. Purchased, inexpensively off-the-shelf, from specialised manufacturers.

## Aqua Transfer Printing

Aqua transfer printing used to apply the decorative finish to the body panels of the Smart car.

Aqua transfer printing (cubic printing) is a decorative finish which is ideal for complex 3D shaped polymers, metals and other materials. The finish uses a printed film to cover the product which can have a range of natural and abstract patterns including wood grain, marbling, leather, textures and abstract designs.

Aqua transfer printing is an immersion process used to provide the product with an eye-popping finish. During the manufacturing process, a printed water-soluble film is set on the surface of water. The film dissolves in the water, leaving the decorative inks floating on the surface, similar to a film of grease. As the product is immersed, the ink film is evenly applied to the piece by the static water pressure. After drying, the parts are coated with a clear protective lacquer. Aqua transfer printing is used in the automotive industry to create mock-timber dashboards and mobile phone fashion covers are also printed the same way.

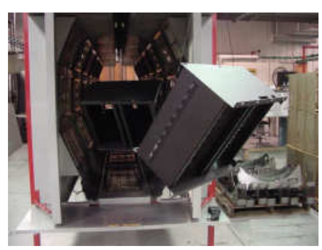
## Powder Coating

Smeg mild steel fridge powder finished in a range of colours.

Powder coating is a finishing process suitable for metal, wood and polymers. It is a dry finishing process which has the advantage that unlike paint it contains no solvents and as a result it is environmentally friendly with up to 98% of the material used due to the recoverable and reusable capabilities of the powder. In addition, powder coatings provide excellent wrap-around coverage and are easily applied. Compared with liquid sprayed coatings, powder coatings can result in a thicker, single coat film build. Finally, the cured coating has an extremely durable finish that adheres well to the component and provides a superior coating hardness along with increased resistance to scratching, impact damage, stains, and chemicals.

The process is usually set up as part of a line production where the components are attached to a moving overhead conveyor where an electrostatic charge is applied. The powder is charged with opposite polarity and is sprayed onto the components. The charged powder particles are attracted to and stick on the surface of the components. The components then move into an Ultraviolet (UV) oven where the powder completely melts and flows out within 2 minutes and finally cures under UV exposure within seconds.

Electrostatic charged powder attracted to the oppositely charged component.



The cured powder coated components move out of the UV oven on the overhead conveyor.

## Varnish & Lacquering

Vacuum cleaner casing spray lacquered on by a robotic arm as it moves along a conveyor belt.

Varnish is a clear or coloured finish applied to timber and manufactured board products to protect and improve appearance while lacquering is a clear finish applied to metals and polymers to prevent tarnishing and scratching.

Varnishing is made up of a combination of oils and resins in any number of variations. Varnishes are typically classified as either oil, synthetic or spirit varnish.

Oil varnish can further broken down into three groupings based on the amount of oil in their make-up: short-oil, medium-oil, and long-oil varnishes. Short-oil varnish dries to a high hardness and can be rubbed to a high gloss sheen, making it a good choice for the fine finisher. Long-oil varnishes resist wear-and-tear best, so they are good for outdoor work and boats. Medium-oil varnishes have a combination of the short-oil and long-oil qualities.

Synthetic varnish is a man-made finish that is the most versatile of the varnishes. Polyurethane varnish is the most common used today. It dries reasonably fast and very tough (it is the most scratch-resistant of the varnishes).

Spirit varnish is made of a solution of natural gum resin. Shellac is the most common gum resin and this comes from shell of the Lac beetle in India.

The application of the varnish depends upon the size and batch volume of the product or component. Small volume production can be finished by manually with the wood sanded by hand with power tools and two or three coats of varnish applied by brush or spray. For volume production the components may be pre-finished by the material supplier using a fully automated system. Here rotating spraying gun technique is used to produce perfectly uniform finish. The process is completed with a water suction unit and mat conveyors for the recovery and the re-use of the varnish before the components are passes through an in-line ultraviolet (UV) oven which rapidly cure the varnish.

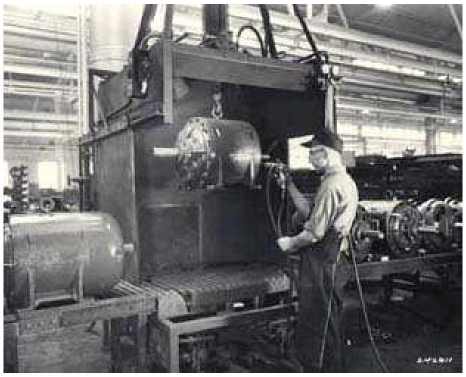
Line production and finishing of kitchen doors. This automated process involves the sanding, spraying and drying of the wooden components

## Painting

Paint is a decorative and protective finish suitable for wood, metals and polymers. Paint can be applied manually by brush or roller; however, these are usually unsuitable for anything other than one-off production. Batch production usually involves applying the paint by spraying. Here the aim is for high transfer efficiency. That is to ensure that a high percentage of paint actually ends up on the product and not lost in overspray. The higher the efficiency, the less coating that is wasted. Factors affecting transfer efficiency include spray equipment type, size and shape of the component, coating type, skill level of the spray operator, air velocity, atomisation air pressure, fluid flow rate and fan size.

Paint is not a particularly environmentally friendly process with the amount of waste material, the nature of certain solvents used to carry the paint pigments and the fine paint spry which is dangerous when inhaled. Depending on the application the paint finish may have to be re-applied every few years and hence it is not always the maintenance free option.

If the entire product is not to be painted then the unfinished areas have to be thoroughly masked.



Industrial finishing of components using spray painting.

## Anodising

The anodising process, performed on aluminium and titanium usually for protection and cosmetic purposes, builds up both on the surface as well as into the metal. The finishing layers are durable and abrasion resistant and can be made in different colours (silver, brass, gold, red, violet, green, blue and black) depending on the chemicals used. The anodised parts are quite durable and do not tarnish and maintain their cosmetic appearance for a long period of time.

Anodised titanium motorbike exhausts.

The aluminium or titanium component being anodised is placed in an electrolyte (commonly of sulphuric acid) solution and used as the anode. When an electrical current is passed through the solution, oxidation takes place and a protective scratch resistant oxide layer forms on the surface.

A selection of aluminium products finished by colour anodising.

Anodised aluminium pipes removed from the electrolytic tank.

## Galvanizing

Galvanizing is a surface finish applied to steel products by immersing them in molten zinc. The zinc coating protects the surface against corrosion by shielding the steel from the moisture in the atmosphere and if the surface is damaged the zinc provides sacrificial protection and prevents rusting.

No other protective coating for steel provides the long life, durability and predictable performance of galvanizing. The hot dip galvanizing process is adaptable to coating nearly all types of fabricated and non-fabricated products such as wire, tanks, crash barriers, hand rails, sheets, strip, pipes and tubes, fittings, hardware, wire cloth, hollow-ware, and structural assemblies.

Small steel components like nails are galvanised by dipping into zinc held in a wire basket.

Galvanised steel crash barriers require no further finish for years of rust free service.

Galvanised steel bins being removed from the liquid zinc.