Manufacturing

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Introduction

How are designs turned into products? What resources, materials and methods used and what set of activities that goes under the heading of 'manufacturing'? This course will introduce manufacturing as a system and will describe some of the many different ways of making products. We will illustrate how the required properties of the materials in a product influence the choice of manufacturing process used.

This OpenLearn course provides a sample of level 1 study in Design

Learning Outcomes

After studying this course, you should be able to:

- explain the difference between industrial and engineering design with reference to familiar products; and for specific products explain whether it is the product's form or its function that enhances its value in the marketplace
- understand the concept of a product design specification (PDS), and be able to indicate some to the factors which should be included in producing one
- describe the role of marketing in developing the PDS for a product
- classify products simply in terms of their basic shape
- describe the difference between the hot and cold working of metals and give the advantages of each.

1 Introduction

1.1 Making a product

In this course you are going to study how designs are turned into products: the resources, materials and methods used; and specifically the set of activities that goes under the heading of 'manufacturing'.

Any design is only useful if it can be made into a product. Remember that an invention is only patentable if it is capable of being manufactured. So there has to be a way of making it, using materials that have the required properties and processes that produce the desired product at a reasonable cost. The design of a product, the materials from which it is made and the manufacturing process route are all mutually interdependent.

1.2 The manufacturing process

Let's first consider what is meant by the term 'manufacturing'. You probably have a general feeling for it already. The word 'manufacture' derives from two Latin words: *manu* (meaning 'by hand') and *factum* (meaning 'made'). We generally think of manufacturing taking place in a 'factory': an abbreviated form of the eighteenth-century word 'manufactory', which came from the same source. So manufacturing applies to artificial products: it does not apply to natural products which grow on the surface of our planet, can be found in the Earth's crust or exist in the atmosphere. On the contrary, such products are the source of what we call *natural* or *physical resources* and which are the starting point for all manufactured items.

Such resources are also often called *raw materials*, but this term is more generally used to describe the input for any manufacturing process. Similarly the term *product* can be used to describe the output of any manufacturing process. So, crudely, a raw material is anything that can be turned into something else and a product is anything for which there is a market. To a mining company, iron ore is a product: it mines its raw material directly from the Earth's mineral resources. An iron producer operating a blast furnace uses this iron ore as a raw material and smelts it into a product, pig iron, in a blast furnace. This pig iron is either solidified for later remelting in engineering foundries or else kept molten and passed on to steelworks. The output product from the blast furnace thus becomes the main raw material for the foundry or the steelmaker. The steelmaker turns the raw iron into steel sheet or bar. These steel products then go on to become the raw material for other manufacturers producing the enormous variety of useful products we see all around us; motor vehicles, domestic white goods (washing machines, refrigerators, etc.), wire coat hangers, pins, paper clips, and every conceivable item which contains steel. Even a tiny spring or a nut and bolt.

Such processing chains are an integral part of the manufacturing route for practically everything our society demands. It matters little whether it be nylon stockings, a plastic moulding for a roof gutter, a child's toy or a tube of adhesive (all of which all start out from oil), or a high voltage electrical insulator for overhead power lines, a spark plug, or a grinding wheel (all of which start out from the same ceramic material, alumina). Every manufacturing chain can be traced back to some natural raw material which has to be put through several, often many, different processes before the desired product is ready for sale in its final marketplace.

Figure 1 shows the raw materials that form part of the manufacturing process sequence needed to produce domestic copper plumbing fittings.

Figure 1 Copper – raw material or product?

The ore is first mined and then smelted into copper, which is usually supplied as rolled bar. Finally the plumbing fittings are produced by combinations of the processes of extrusion and forming (which we will come back to later in this course). Of course, unless you are a DIY enthusiast, you may not even think of the plumbing fitting as the product you use. Central heating parts are bought by the plumber. But for each part of this chain, every person or organisation involved up until the final user will consider themselves to have suppliers of raw materials and consumers of their products.

Exercise 1

All products require raw materials in some form. Identify the raw materials for the following processes: think in terms of the input materials to the process, rather than the original resources.

1. The manufacture of ammonia.
2. The manufacture of ballpoint pens.
3. The manufacture of copper pipe for central heating systems.
4. The manufacture of loaves of sliced white bread.
5. The manufacture of personal computers.
6. The manufacture of Open University course blocks.

Some raw materials are easier to identify than others.

1. Nitrogen and hydrogen.
2. Up to four different sorts of plastic for the barrel, lid, ink tube and plug; brass for the ball holder, tungsten for the ball.
3. Copper, probably as ingots that can be drawn into rods and then into pipes.

4. Flour, water, yeast (plus additives such as vitamins and so-called 'improvers'), plastic film or waxed paper for the wrapping, printing inks, adhesive tape for the closure.
5. Manufacture of PCs is very much an assembly job, so the raw materials are all the internal components, the housings, the mechanical connectors, the connecting leads, etc.
6. Paper, card, staples (or adhesive) and inks, obviously, but do you count the intellectual and creative efforts as inputs?

1.3 Component parts

One thing you will have noticed from Exercise 1 is that several items, such as the personal computer, are assemblies of components made from quite different materials. Others are single objects which need to have a specific set of properties or attributes required for a particular application. Imagine trying to plumb in hot water radiators with rolled-up Open University course blocks, or using copper pipe for the cases of ballpoint pens – in both cases, theoretically possible but practically undesirable! Every artefact has to possess a specific set of properties to suit the intended application. Often these cannot be met by one single material, so most end-use products have to be made up of several different ones.

Exercise 2

Consider the requirements of the application for each of the following and then match up with an appropriate material/product from the list below.

1. Rope for serious mountain climbers.
2. See-through door panel for an electric cooker.
3. Prefabricated roof trusses for a medium-sized house.

Candidate materials and form:

1. High tensile steel wire.
2. Sawn, kiln-dried timber joined with galvanised steel nail plates.
3. Injection-moulded PVC plastic with black colouring.
4. Woven nylon fibres.
5. 6 mm thick toughened glass.
6. Thin-walled copper pipe.
7. Perspex plastic sheet.

1. matches with 4. 1 would be far too heavy, might rust, and would be difficult to grip.
2. matches with 5. Of the others, only Perspex is transparent and this would soften and melt at oven temperatures.
3. matches with 2. Fairly stiff and strong. Try nailing the others!

If a manufacturer concentrates just on processing methods, there is the risk of taking for granted things like the supply of raw materials to the process, the power consumed by the machinery, and the removal of finished products and waste. These are often seen as 'someone else's job'. There are circumstances when this approach is adequate. But engineers should be just as concerned about how to supply the process with materials at the right rate and cost, and how to deliver the products to the next process or to the customer at the right price. Only by doing so can they recognise and respond to important changes in the manufacturing environment brought about by legislation, currency exchange rate fluctuations, new markets and so on.

One thing that distinguishes humans from the rest of the animal kingdom is the ingenuity to devise tools and use them to achieve a purpose. The component parts of the large machines that can be seen in manufacturing plants are made by other machines and these in turn are made by others. They are all 'tools', and one tool is necessary to make another; in other words, all tools are themselves manufactured products. Indeed, most products that are manufactured have evolved from what has gone before, and all stem from the natural materials and resources on the Earth. The challenge to the engineer's ingenuity is to use these resources to the advantage of society. This can be done by understanding the properties of the natural materials and those materials that can be produced from them, such as ceramics, metals and plastics, before converting these into useful artefacts. Doing this efficiently and economically, with minimum waste of energy and materials is what manufacturing is all about.

We will now look at manufacturing as a broad engineering activity, and also at some of the details of manufacturing processes, to show the myriad ways in which raw materials can be turned into the products that we see around us.

1.4 What is manufacturing?

Manufacturing is a very broad activity, encompassing many functions – everything from purchasing to quality control! Later, we will concentrate on some of the manufacturing processes used to convert materials into products. But before doing this it is worth touching on some of the wider issues involved with running a successful manufacturing operation.

To consider manufacturing as a whole we clearly have to look beyond specific sets of materials and processes that lead to single products. Viewing manufacturing as a system provides a way of identifying which factors, whether internal or external, are important, and so aid decision making about choosing a particular manufacturing process in a particular situation.

This may sound needlessly complex, but is it? Sometimes the choice of which material and which process to use will not be trivial. Factors such as consumables for the manufacturing equipment, the amount of scrap produced, the speed of the process, the energy required, and so on, all may need to be considered in order to make a sensible decision about the best way of making the final product.

It is usual to consider both design and manufacture as part of the same manufacturing system. A typical systems diagram for such a holistic approach is shown in Figure 2.

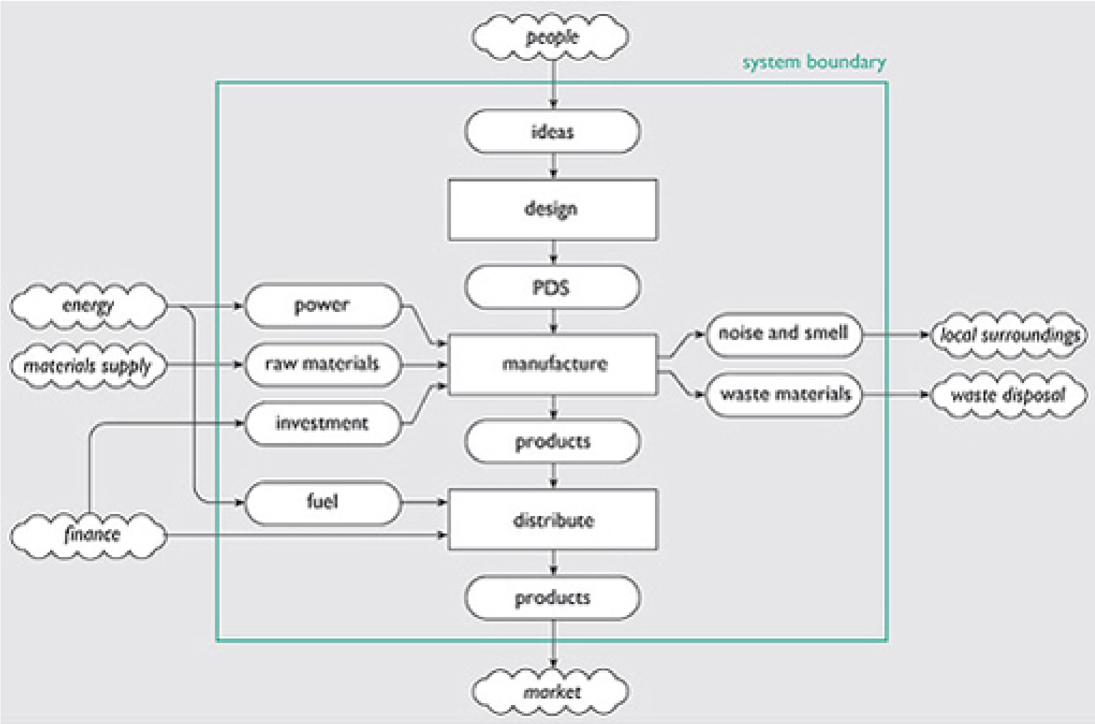

Figure 2 The manufacturing system

In Figure 2, the arrows are showing *flows* – flows of resources, such as power, or the flow of ideas involved in the design process – the resource moves from one box to the next on the diagram. The arrows are not showing influences as in the multiple-cause diagram. Figure 2 is an example of a *process flow diagram*. It tries to describe the whole activity of manufacturing a product, from the initial idea through to delivery of the product to the customer; having designers as part of the manufacturing operation or manufacturing engineers being part of the design team is largely irrelevant. What is important is that design and manufacturing are not separate activities but must interact. A useful way to describe this interaction is shown in Figure 2 as the *product design specification* or PDS.

1.5 Product design specification (PDS)

We can model the production of the PDS for a given product using a process flow diagram. One example of such a diagram is given in Figure 3.

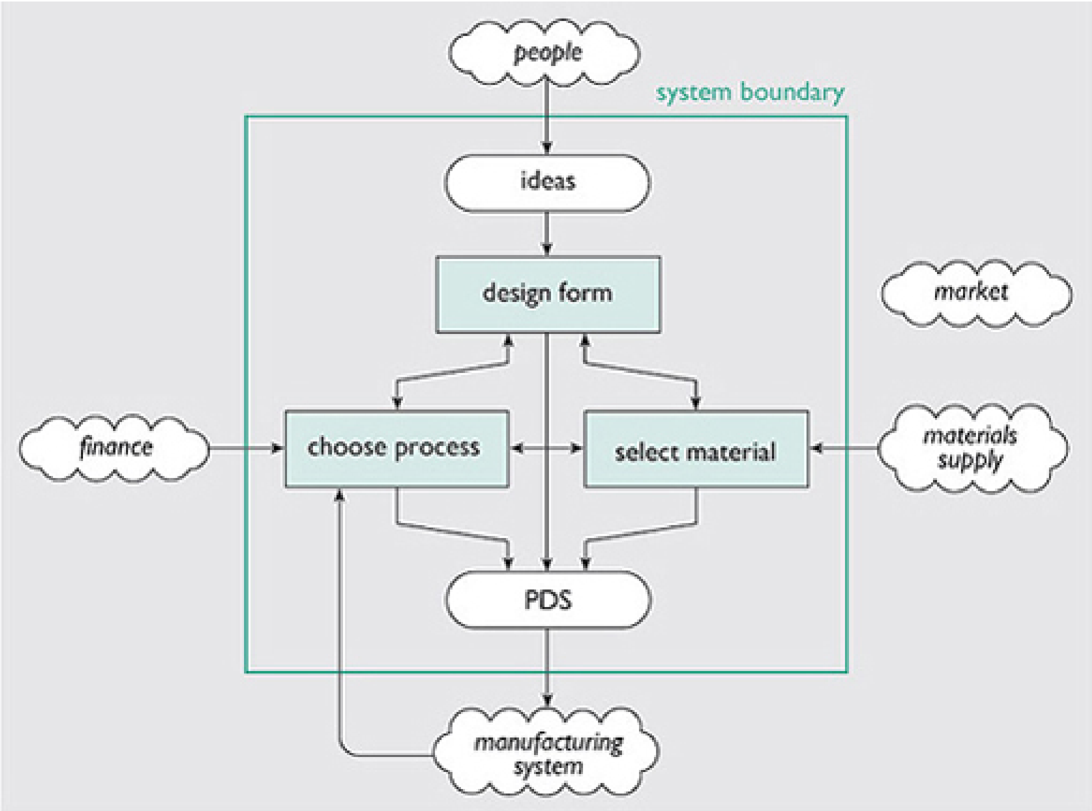

Figure 3 A product design sub-system

This diagram assumes that a conceptual design for a product already exists and so concentrates on how we resolve the conflict between the shape of a product, the choice of material and the selection of a process to make it. It is clear that the output of any useful design system should be a specification detailing the way in which the product is to be made, and the standard to which it is to be manufactured. Such a specification will take into account the company's manufacturing capability, the relative performance of candidate materials, the behaviour of the market and many other technical and commercial factors.

The design activity is triggered by an idea for a product. However, there is not usually much point making a product if you can't sell it so the idea is usually coupled with information concerning the market and expressed in terms of a *market need*. The market need is defined by the PDS which evolves with the product, starting out as the expression of often only a vague idea but gradually increasing in complexity and detail as the product design takes shape. One approach to ensuring a comprehensive PDS is the use of a PDS checklist.

It would be a mistake to think that this checklist is a prescription to design solutions. The important thing to realise is that the PDS increases in detail as the design becomes progressively refined and each of the questions in the list will have to be asked on a number of occasions, the answers becoming more comprehensive on each iteration. One attempt to describe this iterative development of the PDS uses the spiral design model, as shown in Figure 4.

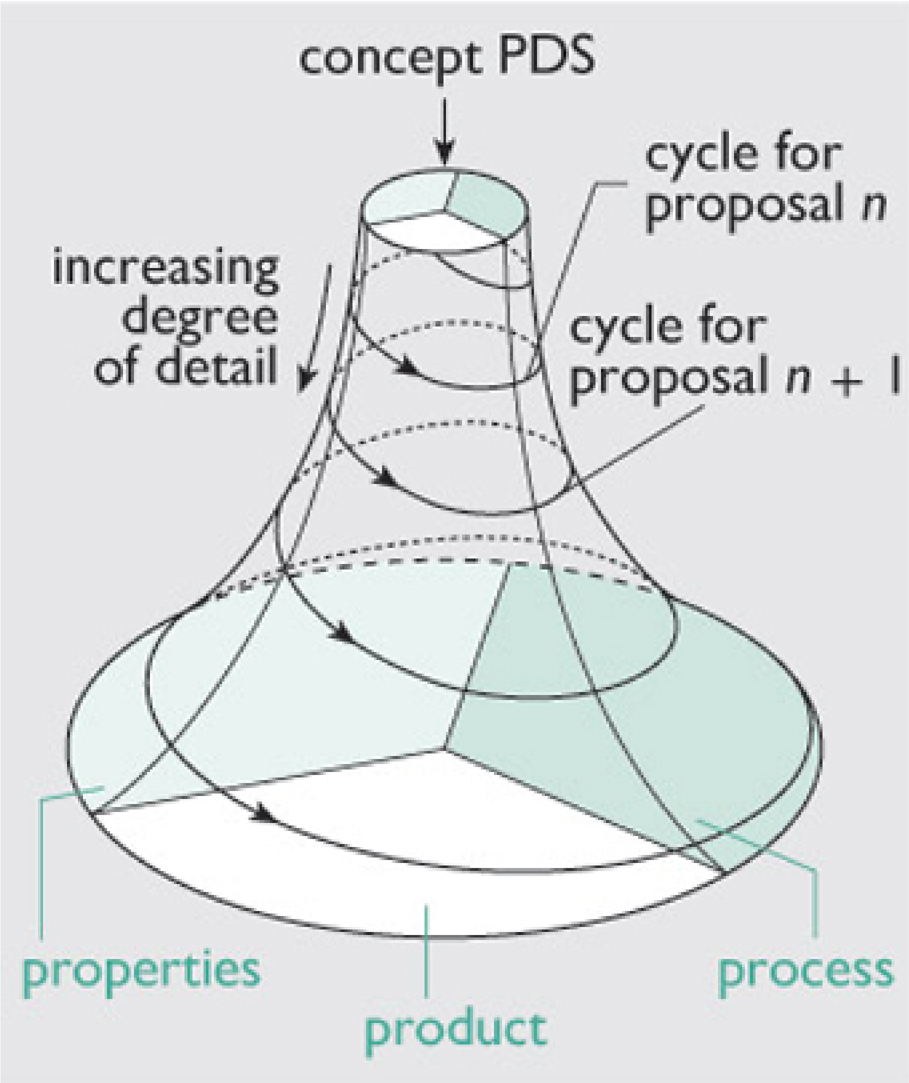

Figure 4 A spiral design model of PDS development

Here the idea of needing to reconsider the three areas of product shape, material properties and process capability is repeated. The increasing size of the spiral represents the fact that the amount of detailed information on the PDS grows with each iteration.

Inevitably, the parts of the PDS you consider important depend on your viewpoint and purpose. Consider, for example, the contrasting viewpoints of an engineer who works for a foundry and is trying to use up spare manufacturing capacity profitably, and an aeronautical engineer working on a new form of anti-stall flap for an airliner. Product teams with expertise in engineering design, marketing and production are required if a balance is to be maintained through the design activity. The leader of this team, often known as the *product champion*, will be chosen for his or her particular skills depending on the nature of the product. The one skill, however, which is always needed by such a person is leadership.

1.6 A PDS checklist

The product design specification, or PDS, should contain all the facts relating to the product. It should not lead the design by presupposing the outcome, but it must contain the realistic constraints on the design. This list is one attempt to cover the principal questions that need to be answered in formulating a PDS. Inevitably, it isn't comprehensive; specific products will require their own additional items.

1. **Performance**

   At what speed must it operate?

   How often will it be used (continuous or discontinuous use)?

   How long must it last?
2. **Environment (during manufacture, storage and use)**

   All aspects of the product's likely environment should be considered: for example temperature, humidity, risk of corrosion, vibration.
3. **Target product cost**

   This is strongly affected by the intended market.
4. **Competition**

   What is the nature and extent of existing or likely competition?

   Does our specification differ from the competition?

   If so, why?
5. **Quantity and manufacture**

   Should it be made in bulk, in batches, or as individual items made to order?

   Does it have to be a particular shape?

   Can we make all the parts or must we buy some in?
6. **Materials**

   Are special materials needed?

   Do we have experience of working with the likely candidate materials?
7. **Quality and consistency**

   What levels of quality and consistency does the market expect for this product?

   Does every product have to be tested?
8. **Standards**

   Does the product need to conform to any local, international or customer standards?

   Is the product safe?
9. **Patents**

   Are there any patents we may either infringe or register?
10. **Packaging and shipping**

    How will the product be packaged?

    How will the product be distributed?
11. **Aesthetics and ergonomics**

    Is the product easy and fun to use?

    Is it attractive to the right customer?
12. **Market constraints**

    Does a market already exist or must it be created?

    What is the likely product lifetime?

    How long do we have to get the product to market?

    What are the customers' likes and dislikes?
13. **Company constraints**

Does the product fit in with company image?

Are we constrained in material or process choice?

Are there any political considerations?

1.7 Product form and function

Another important aspect that affects the balance of the PDS is the relative importance of a product's form compared with its function. These attributes of a product are often ascribed to two subdivisions of the design discipline: engineering design or industrial design.

The amount of attention given to the function of a product compared to its form will depend very much on the nature of the product and its market. Every product has some functional requirements. We are perhaps most concerned that the brakes on our cars do not fail, our clothing does not fall apart or our cups do not leak. Even a work of art, say a painting, has a series of important functional criteria to meet. For example the canvas and frame must be stiff and robust enough to hold the painting securely and the paint itself should not run or discolour with time. But what makes a painting attractive is not usually the quality of its construction and execution but rather its appearance. If I were to paint something it is unlikely that you would be prepared to pay me enough to cover even the raw material costs, so it is clear that in this instance it is the form of the product that adds value to it.

At the other extreme, a gearbox for a motor car has to meet very many functional requirements to fit into the rest of the car, and its looks are of less importance. A buyer of a gearbox will be much more concerned about how well it performs its engineering function than how it looks. In all products, however, it is a case of meeting the functional requirements first and alterations to the form, to add value if necessary, can only be carried out within the constraints imposed by those functions.

1.8 Product design

Clearly, an important part of the design activity is designing a product that will sell, and several of the items in the PDS checklist concern how the product would be perceived by the potential buyer. So although product design is intimately bound up with materials selection and process choice, decisions about which products to make and which processes to use cannot be divorced from consideration of what the customer wants to buy and what the company is capable of manufacturing. We saw earlier that the starting point for manufacture was a market need. So a company must identify, anticipate or create a market need before embarking on the design and manufacture of a product. This ties in closely with the idea that there is no point making something that nobody wants to buy. So how do we include information concerning the market, and the company's position in it, into the PDS? Again, a useful starting point is a diagram of the manufacturing system and we can redraw the system shown in Figure 3 to include the market as seen in Figure 5.

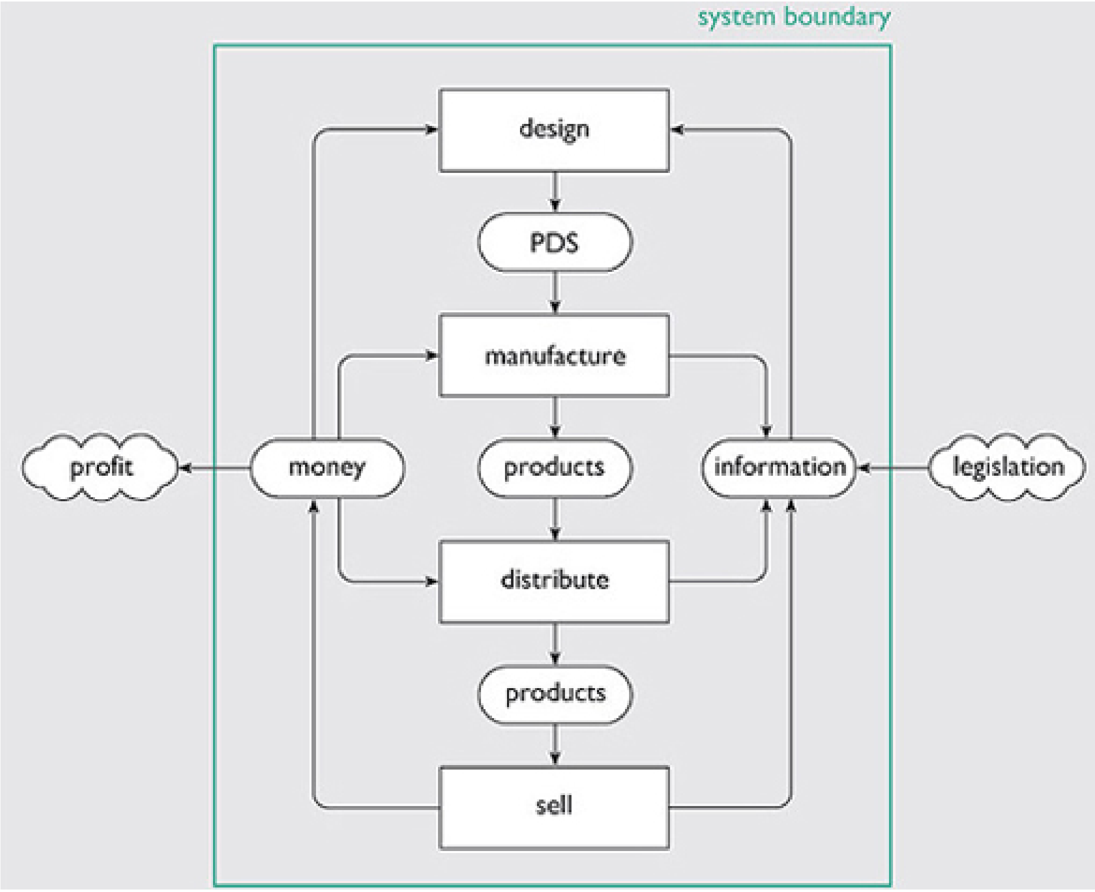

Figure 5 An expanded manufacturing system

1.9 Engineering or industrial design?

Design is commonly split into two distinct but connected disciplines, *engineering design* and *industrial design*. Engineering design concentrates on the factors in the PDS which concern the *function* of a product. That is, whether or not it will perform mechanically, electrically, thermally, etc., the functions defined in the PDS. Industrial design addresses the *form* of the product. That is, everything affecting the interaction between product and its user or buyer, from how it appears in the sales literature or in the shop window, right through to how it is used. Thus industrial design takes in aspects such as the product's shape, colour, decoration, packaging and so on, in the light of such subjective factors as 'style' and 'image' which are extremely difficult to define. In very general terms, engineering design aims to make the product work; industrial design aims to make it sell.

There is still a widespread misconception, especially among engineers, that industrial design is purely concerned with fashion, but this view fails to account for the fact that design effort needs to be expended on, for example, the position, size and shape of control knobs on machine tools. The engineering approach might be to place them in the position most convenient for manufacture and not to consider that their feel and appearance affect how easy an operator finds the machine to use – a big factor in the company gaining repeat orders. So, attention must be paid to both engineering design and industrial design if successful, profitable products are to be developed.

SAQ 1

Which of the following products rely more on industrial design than engineering design for successful sales?

1. A screwdriver.
2. A television set.
3. A car.
4. A light bulb.

Answer

1. The screwdriver simply has to perform a particular function. There is little variation in design between different brands, so the industrial design aspect is clearly unimportant.
2. A television set is likely to be bought because of its aesthetic qualities such as the styling of its case for example, if it is assumed that different brands have roughly the same performance, for example in terms of picture quality. So the industrial design is more important.
3. Again, a car is likely to sell on looks as well as – if not more than – function, so industrial design is important, like the styling for the Aston Martin *Vanquish*.
4. A light bulb is bought solely for function. Industrial design has very little importance, particularly as the fittings are standardised.

1.10 Marketing

The Institute of Marketing defines marketing as:

> the management process responsible for identifying, anticipating and satisfying customer requirements profitably.

Thus the marketing discipline covers those activities which identify what potential purchasers of products or services are looking for, who the potential customers are, what prices might be appropriate, and what method of sales, distribution and promotion might be applied. (Do not make the common mistake of regarding marketing as the same thing as 'sales' or selling. Selling is just one of the functions of marketing.) But the definition also tells us that marketing is responsible for satisfying customer requirements, so it must also instigate and coordinate new product development.

A new product could be the result of any of the following.

- A good idea which perhaps anticipates a market need or exploits a new material or process. (The design concept for the first plastic jug kettle was generated by a firm of design consultants who approached a number of potential manufacturers including Redring. It was innovative in terms of both shape and material. There was not already a defined market for such a product.)
- A need established from analysis of the market.
- The necessity to counter action by competitors. (The explosion in the range of kettles and their different features since the introduction of the first jug kettle exemplifies the response of an old, established industry under siege from new

competition; once one manufacturer has introduced such a product the others must follow suit or risk being left behind.)

- A response to other threats such as new legislation. (The development of lead-free solders is a prime example of such pressures.)

Once the need or idea for a new product has been identified, the organisation must decide what action to take. Since ultimately success depends on getting the right product to the customer at the right place and the right time, the things that need to be considered can be grouped into four convenient categories known as the four 'Ps':

1. How to design, develop and manufacture the *product*.
2. Its *price* in the market.
3. The method of getting it to the customer – the *place* at which it is sold.
4. The method of *promotion*.

The '4 Ps' used to emphasise the role of marketing – *product, price, place, promotion* – define the key elements embodied in a PDS which take us out of the area of simple nuts-and-bolts design of a product and into that of the commercial considerations which are so important for a product's success.

The functions of gathering, interpreting and disseminating information about the state and requirements of the market are crucial to the development of a complete PDS and a successful product.

1.11 Product value

What a marketing perspective provides is information to help the manufacturer to sell products in the market at an identifiable target *price*. The price might just cover the manufacturing *cost* of the article, including the material costs, labour costs, directors' salaries, land rent, bank charges and everything else which involves the company paying money out. Alternatively it might exceed the manufacturing cost, in which case the company makes a profit, or it might be less than the cost, and the company must subsidise the product manufacture from some other activity. This occurs more often that you might first think. In most countries it is possible to buy a mobile phone for much less than its manufacturing cost. The supplier makes its profit from the use of the phone and not from its original purchase price. Even high-technology products such as aircraft engines are sometimes sold at a loss by the manufacturer, which then makes its profit through maintenance and charges for spares for the engine during its lifetime.

But for the product to be bought by the customer at the target price, it must have a *value* to the customer which is at least equivalent to that price. If the value of the product, in this sense, is higher than the manufacturing cost, the firm is said to have added value to the raw materials during manufacture and the product is termed a *value-added* one. Value-added products are worth more to the buyer than they cost the manufacturer to make and, in practice, the value need bear no relationship to the manufacturing cost of the product whatsoever. If one product is bought in preference to another equivalent one of the same or a lower price, it must have a higher value in the eye of the customer. Most manufacturing industry aims to make a profit and it must therefore find ways of adding value to its products to make them seem 'a good buy'.

Much of the perceived value of products is a function of the design of the product – hence the adage 'good products sell themselves' – and in how it is presented to the customer (you only have to think about the premium price commanded by the shape and packaging associated with chocolate Easter eggs to appreciate that point!).

There is also a link between the value added to products and the numbers in which they are made. The nature of the competition in the various areas of manufacture means that as the volume of production increases, the added value tends to decrease. What's more, it is clear that you could make more money by making £1 profit on every one of a million items sold than by making £100 on every one of only a thousand products even if the products had the same market price. So making things in larger numbers, as long as the market exists for them, allows you to work at reduced added value.

Our wide view of manufacturing has shown that the decisions made by an individual manufacturing operation can be affected by its business environment as well as engineering issues. However, whatever the circumstances, decisions must be made about product design, material selection and process choice. So we will now concentrate on the specifics of turning materials into products and the principles behind the processes used.

SAQ 2

Describe briefly how a simple PDS for a wristwatch might develop through the conceptual and detail stages involved in its design. *Hint:* try considering:

1. the shape of the product (draw a simple sketch);
2. the type of use you expect it to be put to;
3. the market you are aiming at (likely selling price and numbers you would like to sell).

Answer

During the conceptual design stage, different solutions to the need defined in the PDS would be explored. In the case of a wristwatch, presumably the need is 'a portable method of telling the time'. It is conceivable (just!) that a free thinking design team might consider portable strap-on sundials or watches based on egg-timers! More realistically, the discussion will be heavily constrained to more modern solutions, so that the conceptual design stage might consider options such as the type of movement to the employed (clockwork or quartz) or whether the watch face should be digital, analogue or both. Decisions on the type of user, i.e. male, female or child, might also be considered at this stage. So would decisions on whether its main use will be functional, in which case it may need additional features, e.g. alarm, stopwatch, etc., or for decoration, in which case features as basic as numbers on an analogue face may be dispensed with.

The detail design will concentrate on the engineering and industrial design of the watch. Engineering aspects will concern the design of the strap attachments and the degree of shock and water resistance as well as decisions on material selection and process choice, not forgetting the important aspect of ergonomics which will involve making the watch easier to use (remember the early LED watches that you needed both hands to use, one to attach the watch to and one to press the buttons?). The industrial design will concentrate on making the product attractive to the end user and, of course, will depend on the market sector at which the watch is aimed.

SAQ 3

What is the role of marketing in defining a PDS?

Answer

The role of marketing is to identify the market need for the product and, from this, to define the product's functional requirements. The formal aspects of the product are also largely decided according to the tastes and needs of the customer. These are converted into shape and materials specifications by the various engineering functions in the company, which in turn also decide processing requirements, taking into account the capabilities of the company. Marketing can have a vital function in ensuring that all the relevant information is passed on to the right people and that the developing product design specification does not evolve away from the initial market needs of the product.

1.12 Manufacturing processes: making things

We can't hope to cover all the manufacturing processes that exist, so instead, you'll meet a selection of some of the more important ones. This should allow you to appreciate the main principles involved and, in particular, how process choice is intimately bound up with product design and material selection.

As you work through the text, you should be asking yourself what processes could have been used to shape the materials involved in making familiar articles such as the pen. You might also ask what the difference is between one example that costs a few pennies and another that has a price tag of several pounds.

It will be helpful if we base our look at manufacturing processes on a specific example. We need a fairly simple product, but one that can be made from a variety of materials that in turn require a range of processes.

The product I've chosen is a simple gearwheel from a food mixer. Why use this example? There are several reasons:

- It's a product that is easily understood;
- there are several different routes by which it could be made;
- gearwheels are products found in myriad applications.

Food mixers tend to be more robust than processors and blenders, to cope with mixing stiff dough and the like, so their gears will have endure higher loadings than the others. As a consequence, their technology is likely to be a bit more demanding. This is another good reason to focus on a gearwheel from a mixer.

In a food mixer, there is a single motor that drives one or two shafts to which the attachments are connected. These interchangeable attachments are fitted to one end of a series of toothed gearwheels, known as a gear train (see **Gears and gearing**), the other end of which is coupled to the electric motor. We're going to look at just one gearwheel in the gear train of a typical mixer (Figure 6).

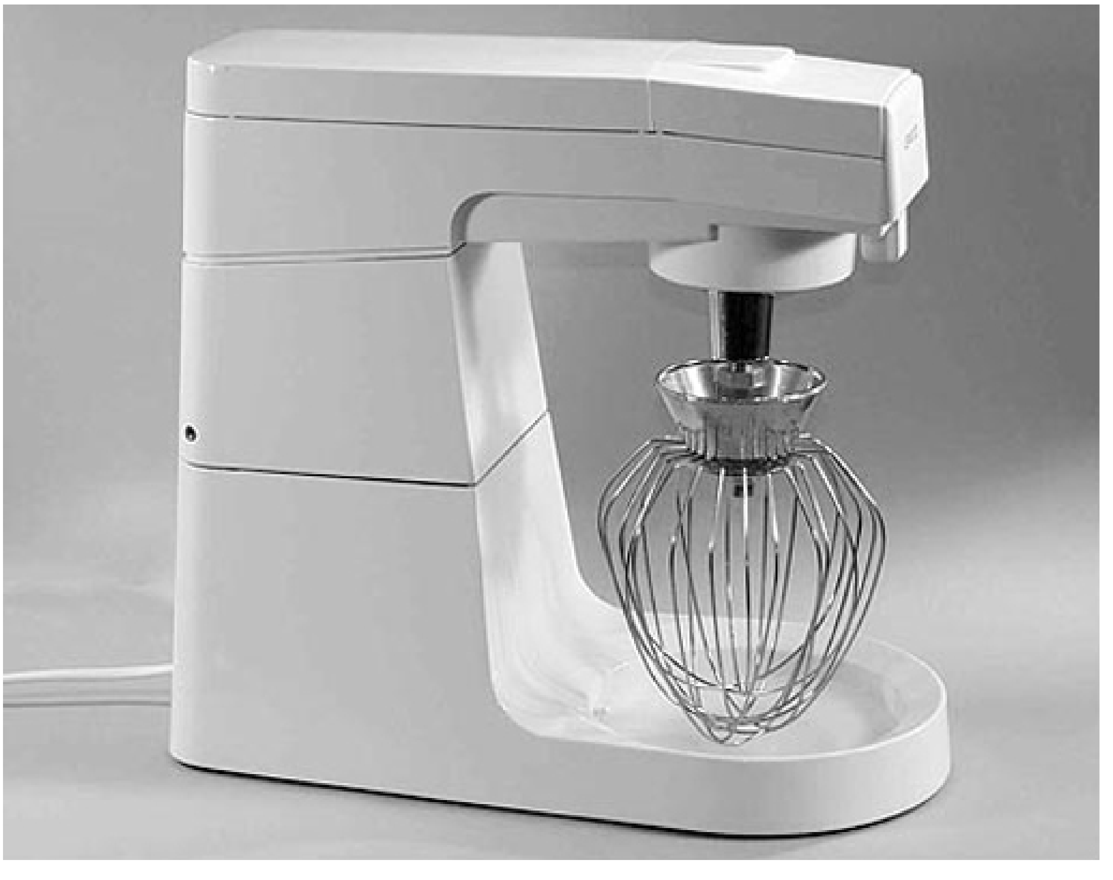

Figure 6 A typical food mixer

1.13 Gears and gearing

Gears and gearing (Figure 7) are a feature of practically all machinery and are by no means confined to food mixers. The function of gearing is to transmit rotary motion and power from one place (for example, a motor) to another (in the case of the food mixer, the tools doing the mixing), usually with changes in speed, direction or both. You'll find gears and gearing in all types of powered transport (including bicycles), in factory machinery and in many household items, from electrical drills to cameras. The gears can either be driven directly from wheel to wheel (by friction or interlocking teeth) or remotely (by belt or chain).

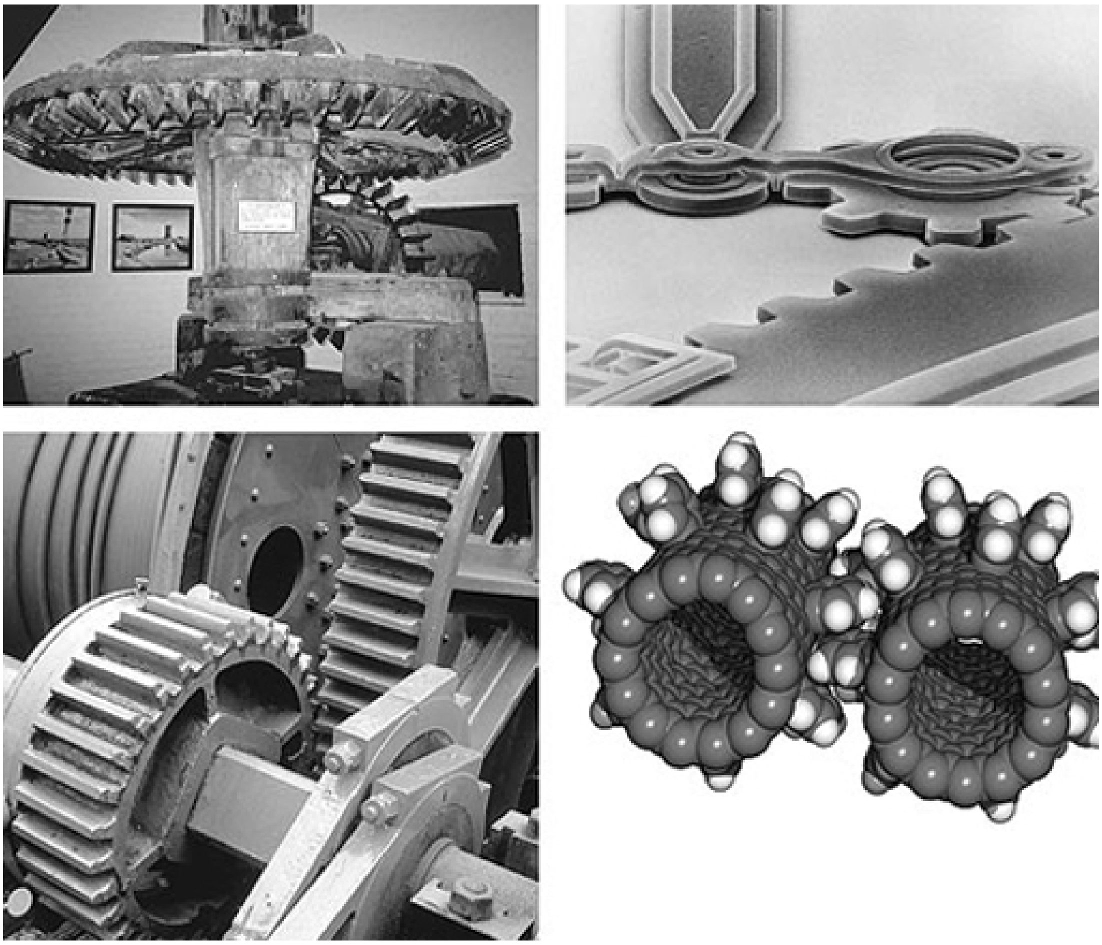

Figure 7 A selection of gears: *top left* wooden gears from a windmill; *bottom left* steel gears from heavy machinery; *top right* gears manufactured using 'micromachining' on a microscopic scale; *bottom right* a theoretical gear built up at an atomic level

So why do we need gears and gearing?

If you've ever ridden a bike, you'll know that it's easier to cycle uphill in a low gear – less effort is needed to turn the pedals. The penalty is that you appear to go more slowly – you need more turns of the pedal crank to cover a particular distance. The situation is reversed when going downhill, so you change to a higher gear. There is a pedalling speed at which your legs can operate most efficiently and comfortably, and the purpose of the gears is to allow your legs to work at that optimum speed.

The same principle applies to an electric motor or car engine. You can't do a hill start in a car in fourth gear, and travelling along a motorway at 70 mph in first gear is unfriendly to the engine!

Let's look at the working of gears in a bit more detail. Figure 8 shows two wheels with their rims in contact. Friction ensures that turning one will cause the other to rotate – they'll act as a pair of gearwheels. If there is no slipping between the two as they move, then, at their contact point, the velocity (v_1) of the rim of gear 1 must equal the velocity (v_2) of the rim of gear 2, i.e.

$$v_1 = v_2$$

But the two wheels have different diameters. If the velocity of their *rims* is the same, they must be *rotating* at different rates. The smaller wheel will complete more than one revolution as the larger wheel turns one revolution, simply because its circumference is smaller.

Rate of rotation is usually expressed either as the number of revolutions in a given time (e.g. revolutions per minute, or rpm) or in terms of a quantity called the angular velocity. Angular velocity is the number of degrees turned in a given time, like 'ordinary' velocity is the amount of distance covered in a given time. Angular velocity is conventionally symbolised by the Greek letter ω ('omega'), and its units are degrees per second (as long as the angles are expressed in degrees).

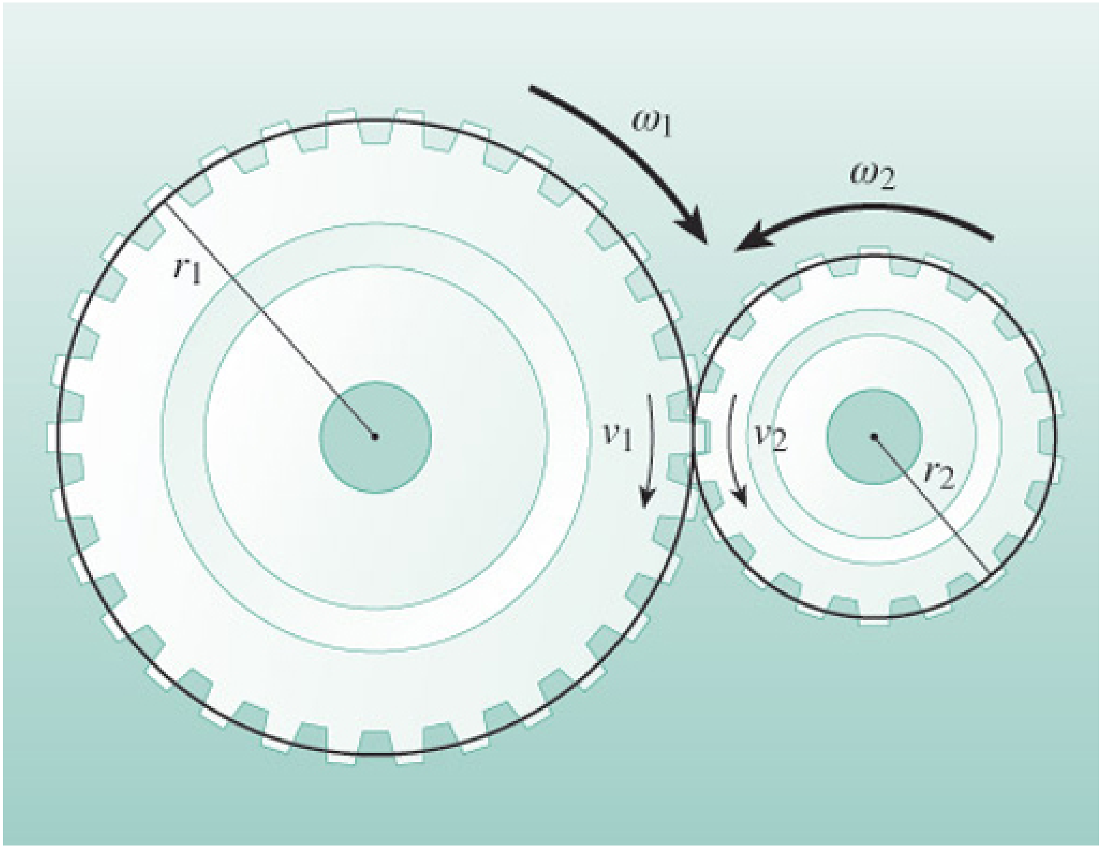

Figure 8 Two wheels in contact

The circumference of a circle with radius r is equal to 2. A wheel with a larger radius will clearly have a larger circumference. If it is being driven from another wheel, then the larger the wheel being driven, the slower it will turn.

In order to work out the angular velocity, we need to work out how many degrees are turned through in a given time. This is all very well, but it would mean that we would always have numbers that are difficult to manipulate cropping up in calculations of angular velocity. So we use another system, which is to describe a circle as sweeping out a number of *radians*.

You can think of a radian as being just like a degree, but rather than there being 360 of them in a circle, there are 2π of them. This may sound complicated, but it has the huge advantage that it makes the maths easier!

Because the circumference is $2\pi r$, and the wheel turns 2π radians in the same time that the circumference is 'moved' this distance, the angular velocity in radians is simply:

$$\omega = \frac{v}{r}$$

For our two wheels with radii r_1 and r_2, we have that

$$\omega_1 = \frac{v_1}{r_1}$$

and

$$\omega_2 = \frac{v_2}{r_2}$$

Since at the point of contact $v_1 = v_2$, combining these two expressions gives

$$\frac{\omega_1}{\omega_2} = \frac{r_2}{r_1}$$

The fraction r_1/r_2 defines the *gear ratio* of this particular system. A similar thing applies to gears with teeth, where the teeth interlock to turn the wheels, the ratio being N_1/N_2 where N is the number of teeth on each wheel. The lower the gear, the lower the value of the gear ratio. Notice also that directly-driven gearwheels like those in Figure 8 rotate in opposite directions to one another.

Gear ratios are the same for indirectly-driven gearwheels (Figure 9), whether by belt (r_1/r_2), or by chain (N_1/N_2). However, as you can see, both gears rotate in the same direction here.

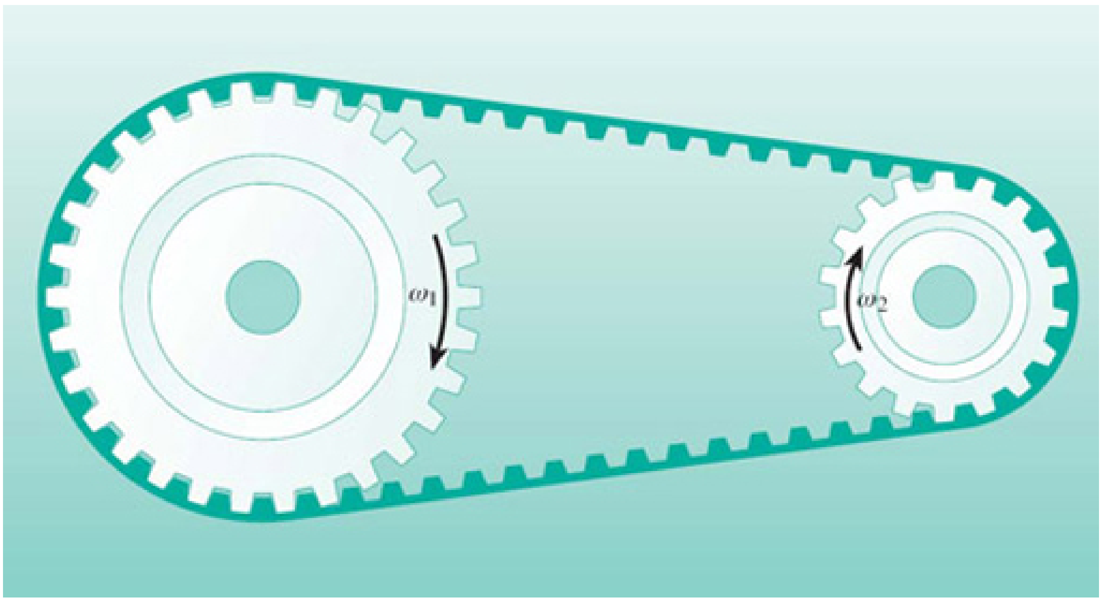

Figure 9 Indirect gearing

Not all manufacturing processes can be used sensibly to make gearwheels, so occasionally we'll look at the manufacturing aspects of some of the other parts which go into making the complete food mixer.

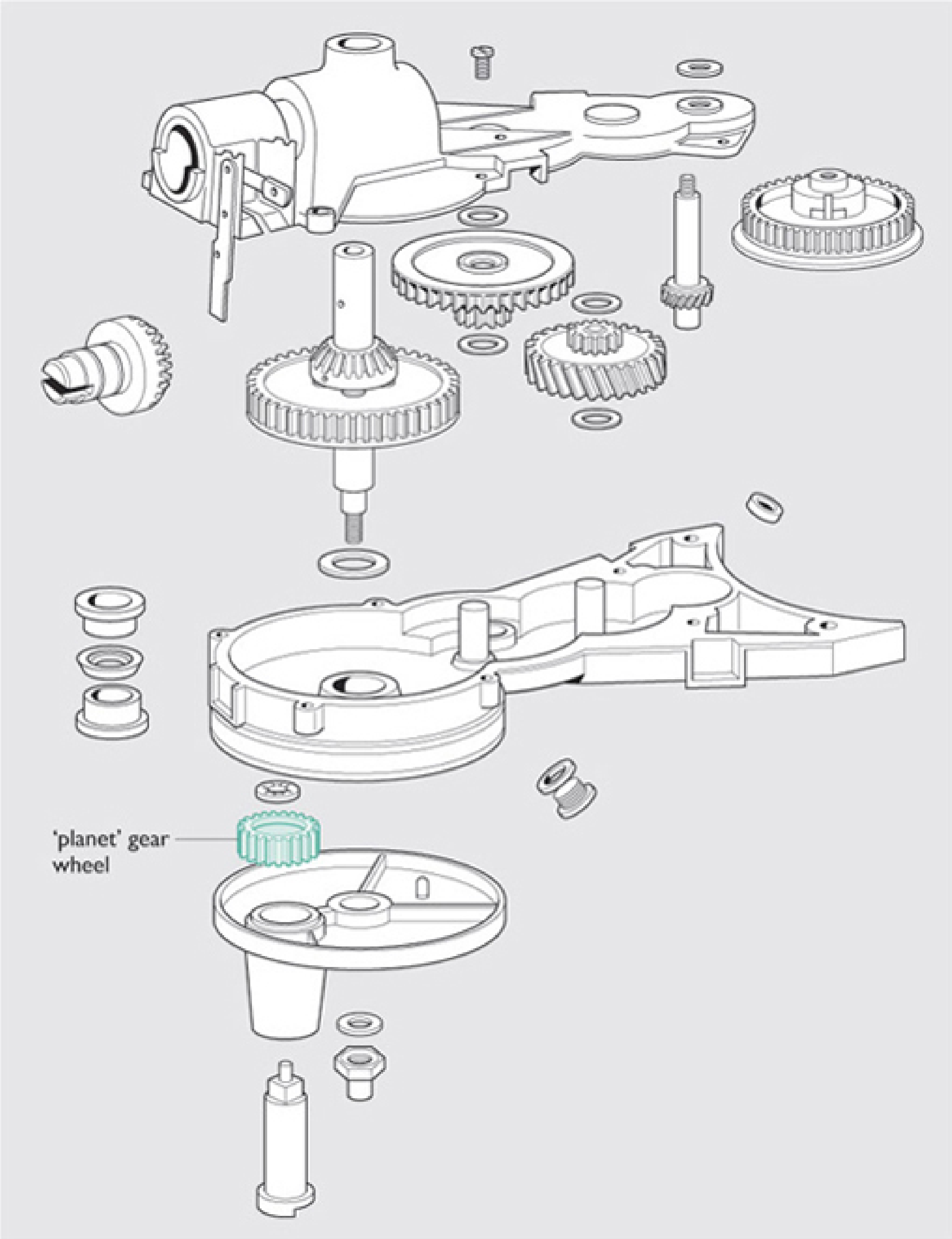

Figure 10 An exploded view of the train of gears in the food mixer

Figure 10 shows an exploded view of the gear train from the food mixer in Figure 6. You can see that this is a fairly complex assembly of intermeshing parts. The complexity arises because not only does the mixing tool spin on its own axis but the axis itself also moves around a circular 'orbit' in the bowl of the mixer. In addition, this particular gear train 'gears down' the motion from motor to tool by a factor of 20. But don't worry about the details of Figure 10. We're going to concentrate on the simplest gearwheel in this assembly, which is known as the planet gear. A photograph of this and its associated static ring gear is shown in Figure 11.

Figure 11 The ring and planet gears

1.14 Getting into shape: some basics

If you think about it, the number of different things you can do to a raw material to get it into a desired shape is pretty limited.

You could melt or liquefy the raw material and *pour* it into a mould that replicates the shape you want – as if making ice-cubes.

You could *squeeze, squash, hammer* or *stretch* the material into its required shape – similar to modelling with clay or Plasticene, or rolling-out a piece of dough.

You could start with a lump of raw material and *cut* it to shape, in the same way Michelangelo transformed a block of marble into the statue of David.

Finally, you could assemble your shape by taking different pieces and *joining* them together using any number of joining methods: *screwing, nailing, gluing, welding* or *stitching* for example – innumerable products are made in this way, ranging from clothing to cars and from computers to aircraft.

So, starting with a given mass of raw material, whether it is a pile of granules of plastic, an ingot of steel, a lump of clay, a block of stone or whatever, the basic process routes for manipulating it into a specified shape are essentially limited to:

1. pouring, which we will refer to more precisely as *casting*
2. squeezing, which we will call *forming*
3. *cutting*, and
4. *joining*.

However, it's not quite as simple as that. To start with, the wide range of engineering materials means that there are many, many variations on each of these process routes. So far we have principally considered materials just to be 'stuff' that has a series of properties. We have seen that these properties vary from material to material but we have not really started to think about why they vary. We are not going to go into the material science behind this in any real depth in this course but what is important to realise is that materials, and hence products, exist on a whole series of size scales. We are all familiar with the sizes of tangible products ranging from a teacup all the way up to a suspension bridge or the Millennium Dome! We can call this scale *macro structure*. You should also be familiar with the concept that the properties of materials are controlled by the type and arrangement of their individual atoms and molecules, usually called *atomic structure*. Much of materials science and engineering is concerned with a size scale in between, too small to be seen with naked eye, but much larger than individual atoms and molecules. This middle ground is termed *microstructure*.

The properties of solid materials can be profoundly influenced by their microstructure and because the microstructure is often changed by processing, the properties of materials, and hence products, are dependent on how they are processed. Examples of these different size scales are given in **Scales of material structured**.

Even where a particular type of material and process combination is feasible, it could just be hopelessly uneconomic to contemplate it as a manufacturing option. Finally, the shape of the product is also important. Some manufacturing methods are better suited to particular shapes than others. Indeed, the shape of a product is a good attribute to begin with when deciding which processes are feasible. So one of the first things we must do is think about how we describe shape. One approach to this problem is given in **Classifying shapes**.

1.15 Scales of material structure

Exactly what influences the properties of a component can depend on many things: We've already mentioned the importance of materials properties and the component geometry, for example.

The component geometry is an example of structure on a *macroscopic* scale. Look at Figure 12(a), which shows the second Severn Crossing. The bridge has the structure it does because it was built to achieve the task of providing a path for vehicles across the estuary, at an acceptable cost and with complete safety during construction and during use. The central portion is an example of a cable-stay bridge, where the deck of the bridge is hung from the supporting cables. This structure was chosen, presumably, as being the best solution.

Figure 12(a) The second Severn Crossing

If we look at the structure of a support cable for such a bridge (Figure 12(b)), we see that it is not a solid bar of material, but is 'woven' from many thinner strands of wire. This structure (still a macrostructure) is chosen for several reasons, including safety, as with a reasonable safety factor, it shouldn't matter if a flaw causes the failure of one wire strand, as there are multiple paths for the load that the cable is supporting. In addition there are some beneficial properties that cable structures have compared to large single strands, such as flexibility.

Figure 12(b) A steel cable

The structure story doesn't stop with the material for one strand, though. I've already indicated that steel is a mixture of iron with carbon, and how the carbon affects the structure of the iron on a microscopic scale depends on the amount of carbon in the iron, and the heat treatment that the iron has had. Figure 12(c) shows the *micro structure* of a typical steel (so-called because we are looking at the steel on a microscopic scale). This shows that as we look in closer detail, we begin to see that what we thought was quite a smooth, plain metal surface has a lot of underlying structure to it. Once we've zoomed in so that we can see features as small as 10 micrometres, it becomes clear that the metal is composed of small individual 'grains'. This structure in turn determines the mechanical properties, like strength and toughness, of the steel. We can change the structure of the iron: through alloying and heat treatment the grain size and structure can be altered, so tailoring the properties of the material that we make.

Figure 12(c) Optical micrograph of steel

Figure 12(d) zooms in still further, showing us more of the structure within the grains themselves. Influencing things at this level is more complicated, but it can be done, and again can help to tailor the material properties.

Figure 12(d) Transmission electron microscope (TEM) micrograph of steel

Finally, we can zoom down to the level of the atomic structure (Figure 12(e)). In this case, we're looking at carbon, one of the elements in steel. The bonding between the atoms, and the structure they take up, critically influences the material properties, but there's nothing we can do to change it! Some materials are more useful than others because they have the right sort of atomic bonding and atomic structure, and a microstructure that we can do useful things with. In Figure 12(e), you can see that each carbon atom is surrounded by six others in an hexagonal pattern. This is simply the way that carbon atoms arrange themselves in this instance (carbon is versatile in that it can adopt several atomic arrangements).

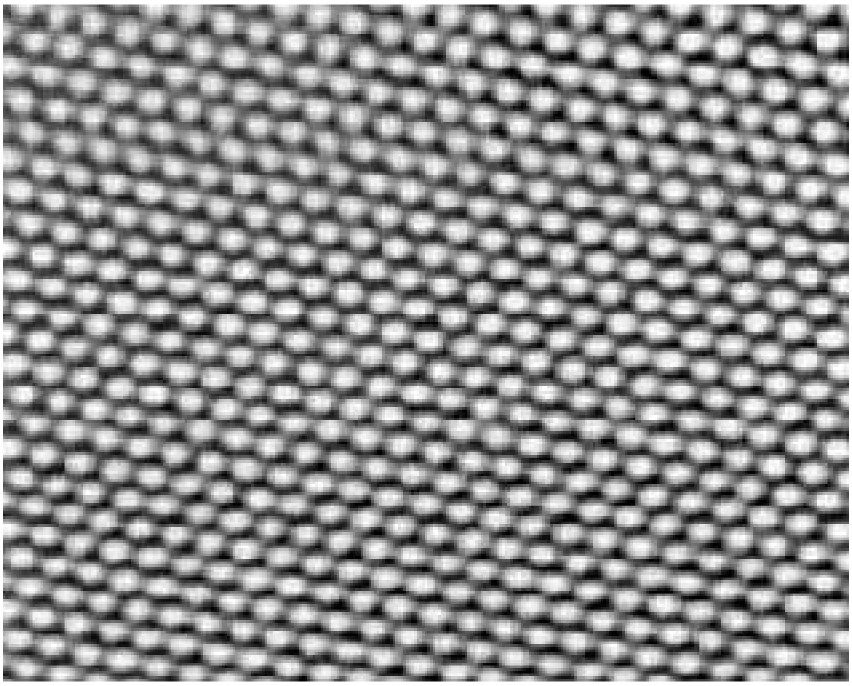

Figure 12(e) Scanning tunnelling microscope image of carbon atoms

We will refer to microstructure frequently in this section. It is a key factor in determining mechanical properties, and it can be greatly affected by the choice of manufacturing process for a material.

1.16 Classifying shapes

1.6.1 (2D) continuous

If the profile of an artefact does not change along its length – like a pipe, electrical cable or aluminium cooking foil – then it can be classified as having a simple (continuous) 2D (shorthand for two dimensional) shape. Many 2D products are used as the raw material for processes which make them into three-dimensional shapes. PVC window frames for example (Figure 13) are made from continuous extrudate (the product of the process of polymer extrusion) which is cut into suitable lengths and then joined together by fusion welding.

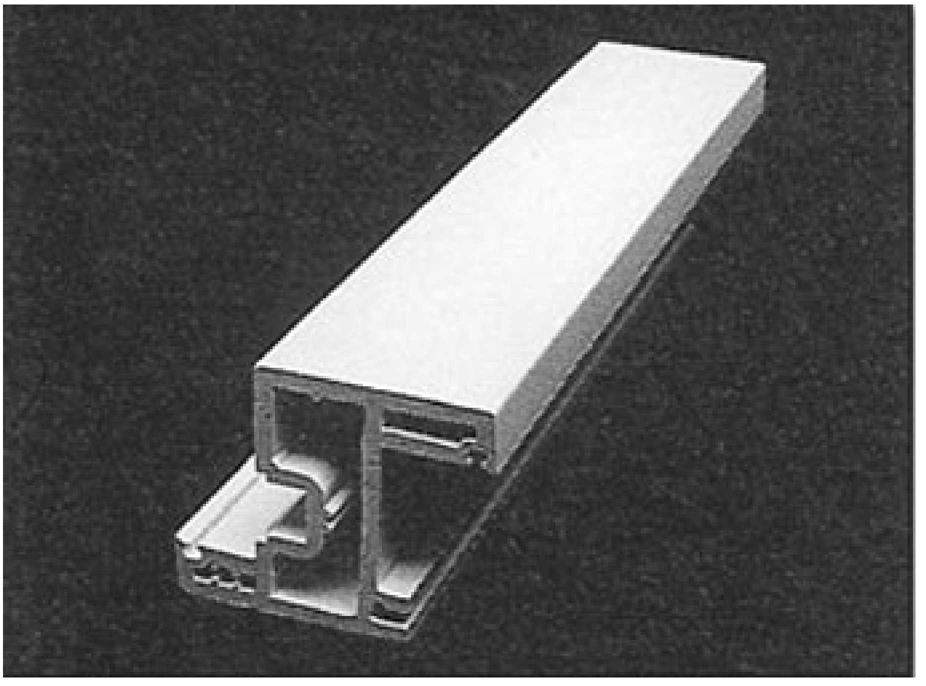

Figure 13 Extruded uPVC window frame

1.16.2 (3-D) - Shapes

Most artefacts have profiles that vary in all three axes. Many processes are suitable for the production of 3D shapes, so we need some further breakdown of this high-level classification. We will split 3D shapes into *sheet* and *bulk* shapes.

Sheet products have an almost constant section thickness, which is small compared with their other dimensions, but without any major cavities. Therefore washing-up bowls and car-body panels (before assembly) are examples of sheet products (Figure 14).

Figure 14(a) Plastic washing up bowl

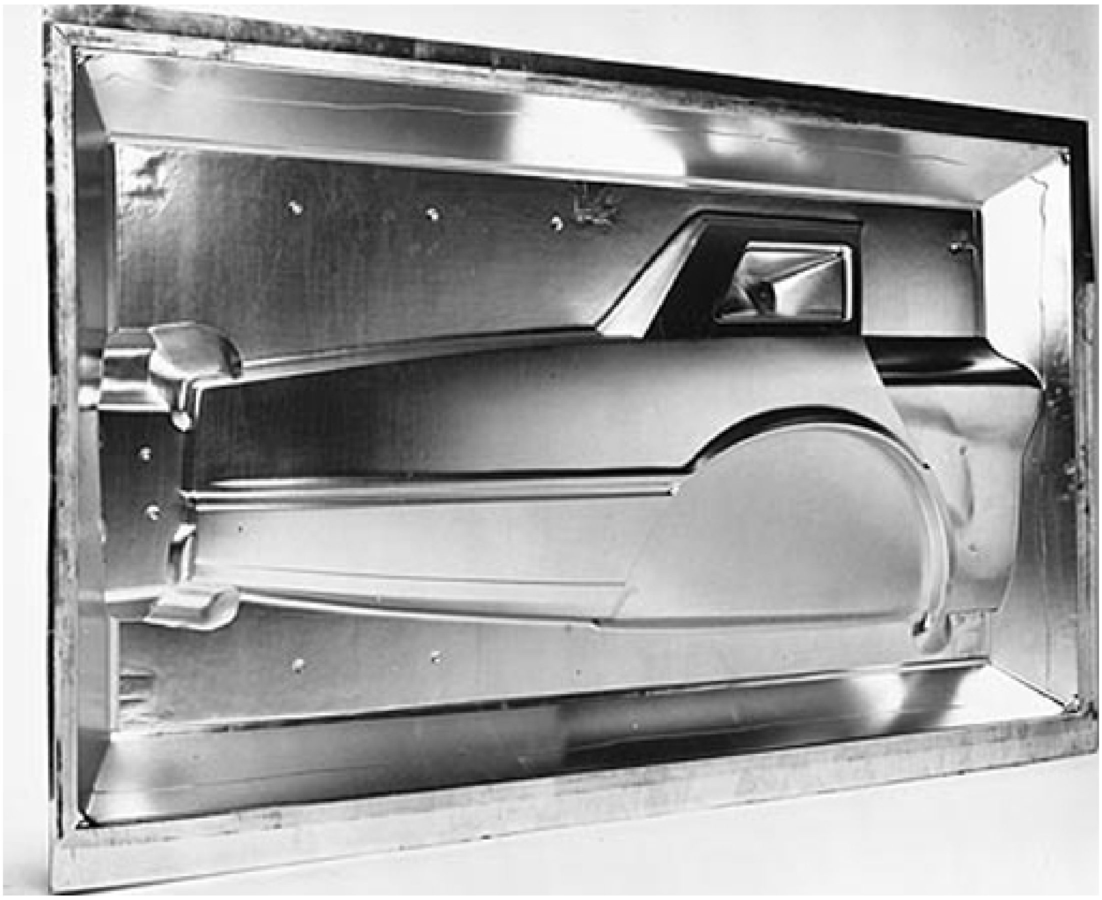

Figure.14(b) Car body panel

The majority of cast products fall into the category of *bulk* shapes, and have complex forms, often with little symmetry. If they have no significant cavities in them we will call them *solid* (Figure 15) but if they do have cavities, they will be classed as *hollow*. The cavities in hollow objects can be quite simple but they can also be more complex, involving re-entrant angles (re-entrant angle: a shape in the mould which would prevent the product from being removed from the mould after solidification), as is the case with the carburettor body in Figure 1.

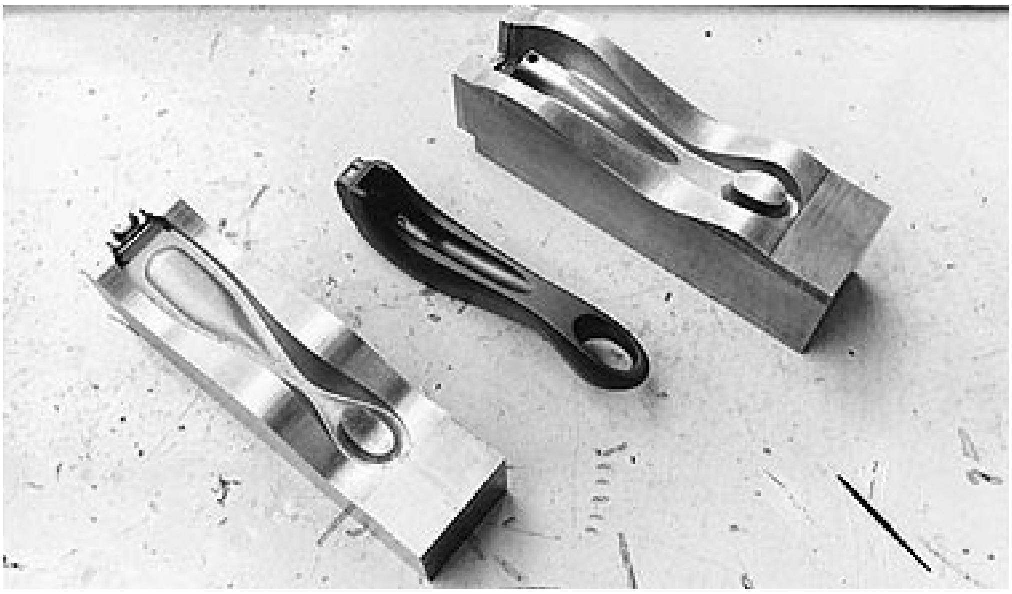

Figure 15 Plastic saucepan handle and its mould

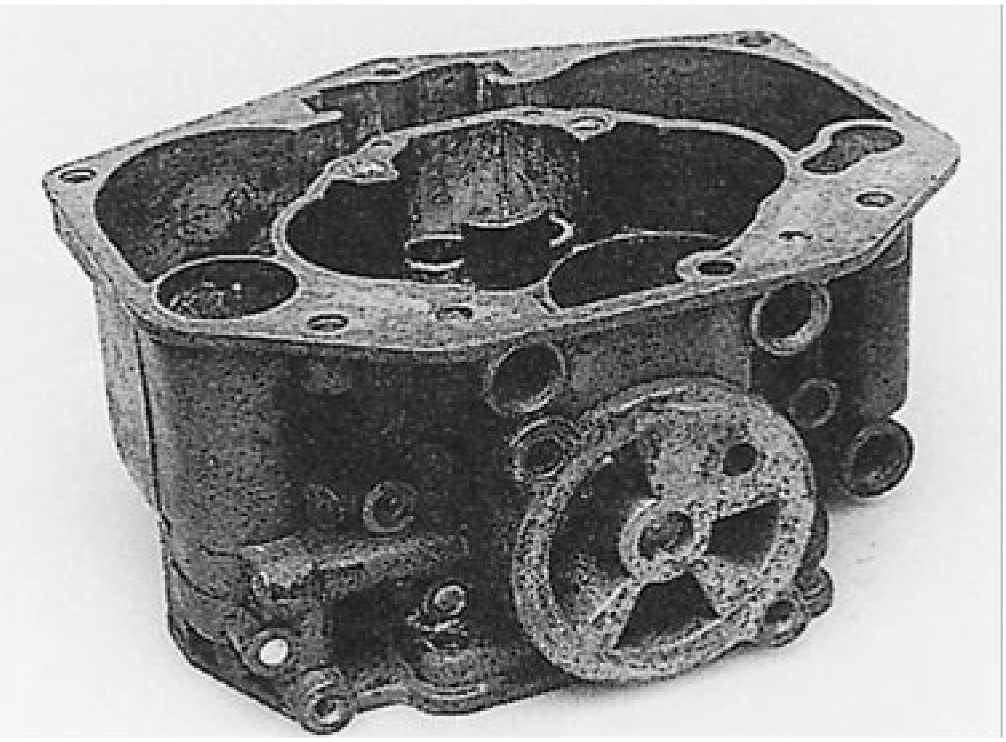

Figure 16 Zinc alloy carburettor body showing complex internal cavities

One way to present such a classification is by using a hierarchical tree diagram. Figure 17 shows such a diagram for our shape classification. A similar presentation is often used to show family trees. You can see that as you progress down the tree, the shape definition becomes more and more precise. One problem generated by this classification of shape is what to do about containers and similar objects. Depending on how you view the exercise, they could be either sheet, since they tend to have uniform section thicknesses, or hollow since they often have cavities which are entirely enclosed within the artefact. We have chosen to classify them as hollow shapes.

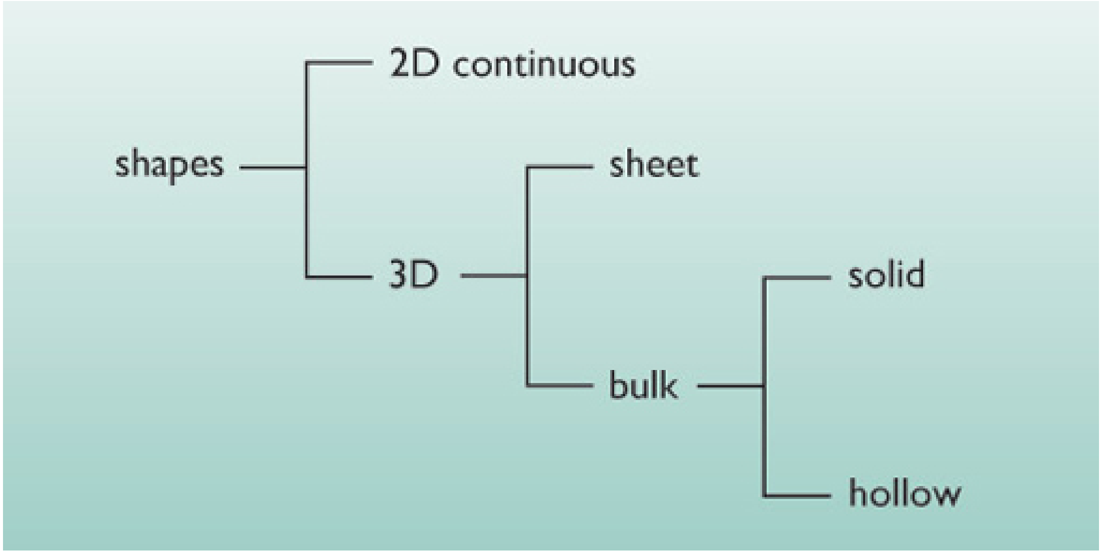

Figure 17 A hierarchical shape classification tree

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Consider the following list of components and artefacts and classify each according to the shape classification given in **Classifying shapes**.

1. A plastic tray used to hold the confectionery within a box of chocolates.
2. A garden hosepipe.
3. An open-ended spanner.
4. A plastic (PET) lemonade bottle.
5. A rail (from a railway track).
6. A flower pot.

Answer

1. 3D sheet.
2. 2D continuous.
3. 3D bulk solid.
4. 3D bulk hollow.
5. 2D continuous.
6. 3D bulk hollow.

We'll now start to look at the different classes of manufacturing processes, and their advantages and disadvantages.

2 Casting

2.1 Introduction

Casting is one of the easiest classes of process to understand. Casting is simply a process where a mould is filled with a fluid, which then solidifies in the shape of the mould cavity. Provided the liquid is capable of undergoing a liquid-to-solid transition, by freezing or chemical reaction for instance, then casting can be used. Making ice cubes and jellies are useful analogies here. The production of the mould is one of the most important stages in making a casting. The casting, when solidified, must be of the right shape for the final product. In making the mould, often a 'pattern' made in the shape of the final component is used. This might be a wooden mock-up, for example.

Complex 3D shapes can be made using casting processes. Casting can be used to make a vast array of products, from gas-turbine blades to cheap plastic toys. Cast parts can range in size from fractions of centimetres and grams (such as the individual teeth on a zipper), to over 10 metres in length and many tonnes (such as the propellers of ocean liners). Using one of the available casting processes almost anything can be manufactured. It is a matter of optimising materials to be cast, the mould material and the pouring method (see **Properties for processing – casting**).

Generally, during casting, the fluid flows into the mould under gravity, but sometimes the fluid may need some extra force to push it into the cavity.

Casting is not restricted to metals (or jellies). Glass and plastics can also be cast using a variety of processes, each being dependent on the raw starting material, and the manner by which it can be made to flow when it is in its liquid state. Casting processes can be classified into three types depending on the nature of the mould used.

2.2 Properties for processing – casting

The casting (or pouring) group of processes is one of the most convenient for making three-dimensional shapes, especially if repeated copies are required. However, you do have to be able to get your material into liquid form, and it has then to be 'runny' enough to be poured.

What do these conditions require?

To get a liquid, you have to either melt the material; or dissolve it in a solvent which is subsequently evaporated off (the 'solution route'); or pour liquid precursors into a mould where they react chemically to form a solid (the 'reaction route').

Some materials (e.g. thermosetting plastics) decompose rather than melt on heating. Others react with oxygen when heated, so need to be melted in inert atmospheres (which may prove expensive). Yet others have such high melting points (see the database) that the energy costs of heating them is only justified in special cases.

The solution route needs a suitable solvent, which you then have to be able to evaporate safely (many coatings such as paints are applied this way), but you can have shrinkage problems as the solvent is removed. The reaction route is used for both thermosets and thermoplastics and for concrete, but chemical reactions can produce considerable quantities of heat, so you must allow for this in the design of the process.

Once you have the liquid, can you pour it?

The physical property that determines the 'runniness' of liquid is called *viscosity*. This varies with temperature and is not all that useful for describing how well a mould will be filled if the temperature of the liquid is falling as it runs into the cold mould. In the casting of metals a more useful property is *fluidity*, which takes into account not only the viscosity changes but also the effects of cooling rate, surface tension of oxide films and the temperature *range* over which the alloy filling the mould actually freezes. Eutectic alloys have a high fluidity as they melt at a single temperature. Many of the alloys used for casting products are based on eutectic alloys.

Water and most liquids at room temperature have low viscosities, so can be poured easily, as can thermoset precursors. Molten thermoplastics, freshly-mixed concrete and clays have much higher viscosities. Although concrete can be poured, the others generally need to be pushed into their moulds, which is why injection-moulding machines for plastics are much 'beefier' than their pressure die-casting machine counterparts for metals.

2.3 Types of casting

2.3.1 Permanent pattern

This type of casting uses a model, or pattern, of the final product to make an impression which forms the mould cavity. Each mould is destroyed after use but the same pattern is used over and over again. Sand casting is a typical example of a permanent pattern process, where a pattern is placed into a special casting sand to form the right shape of cavity. Permanent pattern processes are usually cheaper than other methods, especially for small quantity production or 'one-offs', and are suitable for a wide range of sizes of product.

2.3.2 Permanent mould

In this method the same mould is used for large numbers of castings. Each casting is released by opening the mould rather than by destroying it. Permanent moulds need to be made of a material which can withstand the temperature fluctuations and wear associated with repeated casting. A good example of a product made with methods such of this is the ubiquitous 'die-cast' child's toy ('die' is another word for 'mould').

Figure 18 Die-cast toy

2.3.3 Expendable mould and pattern

With this type of casting, a pattern is made from a low melting point material and the mould is built around it. The pattern is then melted or burnt out as the metal is poured in. The mould has to be destroyed to retrieve the casting.

This method is used to make moulds for casting high melting-point alloys like those used for jet engine turbine blades (Figure 19). A model (the pattern) of the blade is made in wax. The pattern is then coated in a thick slurry containing ceramic particles. The slurry dries, and is then fired in an oven: this hardens the ceramic (like firing a pot) and melts out the wax, leaving a hollow ceramic mould. The metal is then poured in to the mould, which is broken away after the metal has solidified and cooled.

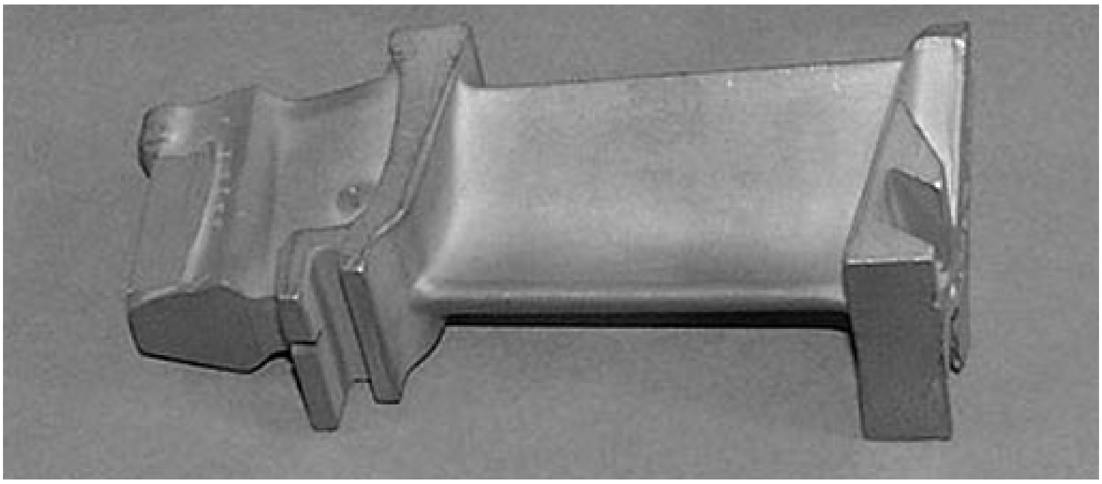


Figure 19 A turbine blade

2.4 Casting processes

Casting is used to produce ingots which are then used as the raw materials for forming processes such as rolling or extrusion. As an intermediate processing step, casting needs to be less carefully regulated (than other processes to make engineering products), as the properties of the final product are controlled by the forming processes which follow casting. Therefore we will concentrate on casting processes which make components.

Casting processes vary depending on the type of solid to be produced and the type of fluid used to fill the mould. The type of mould required depends on the material to be cast, and in particular, on the temperature at which it is sufficiently viscous to flow into the mould. Metals are cast when molten, so we should consider their melting point, whereas for polymers (whose fluidity can change markedly with temperature) we need to know the temperature where viscosity is low enough for reasonable flow.

2.5 Casting metals

Sand casting is illustrated in Figure 20. A solid replica of the required object is made: the 'pattern'. Sand is then rammed around the pattern in a 'moulding box'. When the pattern is removed it leaves a shaped cavity behind. The runners (where the fluid is poured in) and risers (where excess fluid can escape) also act as reservoirs of liquid to top up the casting as the metal contracts on cooling.

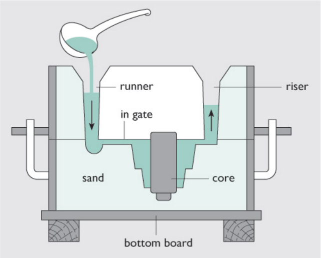


Figure 20 The sand-casting process

The process can be used, perhaps surprisingly, to make hollow castings. To do this, 'cores' are inserted into moulds to produce shapes that would be difficult or impossible to make by just using a pattern.

The mould is destroyed when the solid casting is removed. The surface of the castings produced by this method tend to be rather rough, even though quite fine-grained sand is used for the moulds. So some machining (cutting) of the surface is generally required before a finished product is made from a sand-cast route. Certainly the runners and risers need to be cut away.

Sand casting is particularly useful for casting complex 3D shapes such as automobile cylinder heads or large castings as shown in Figure 21.

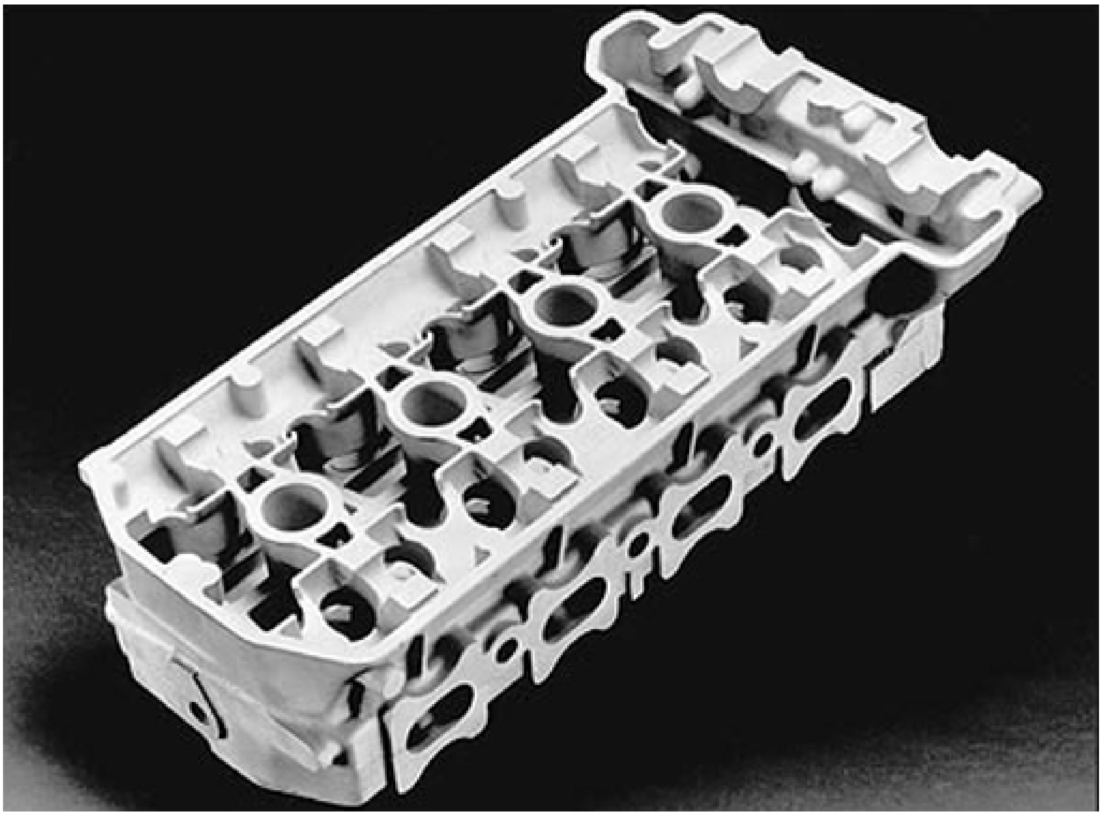


Figure 21 Sand cast (a) cylinder head (b) oil rig joints

Gravity-die casting, Figure 22, is similar to sand casting except that the mould is machined from solid metal, usually cast iron. This means that the mould and cavity are permanent. Being metal, the mould can be machined accurately and, having good thermal conductivity, it allows the casting to cool quickly. The surface finish is better than can be produced by sand casting, but as metal moulds are required, product sizes are generally smaller than those possible with sand casting (because a metal mould will cool the liquid faster than a sand mould would, making it harder to fill the mould evenly if it was too large). Typical products include bicycle cranks and engine pistons. Of course, the metal being cast must have a lower melting point than the mould metal!

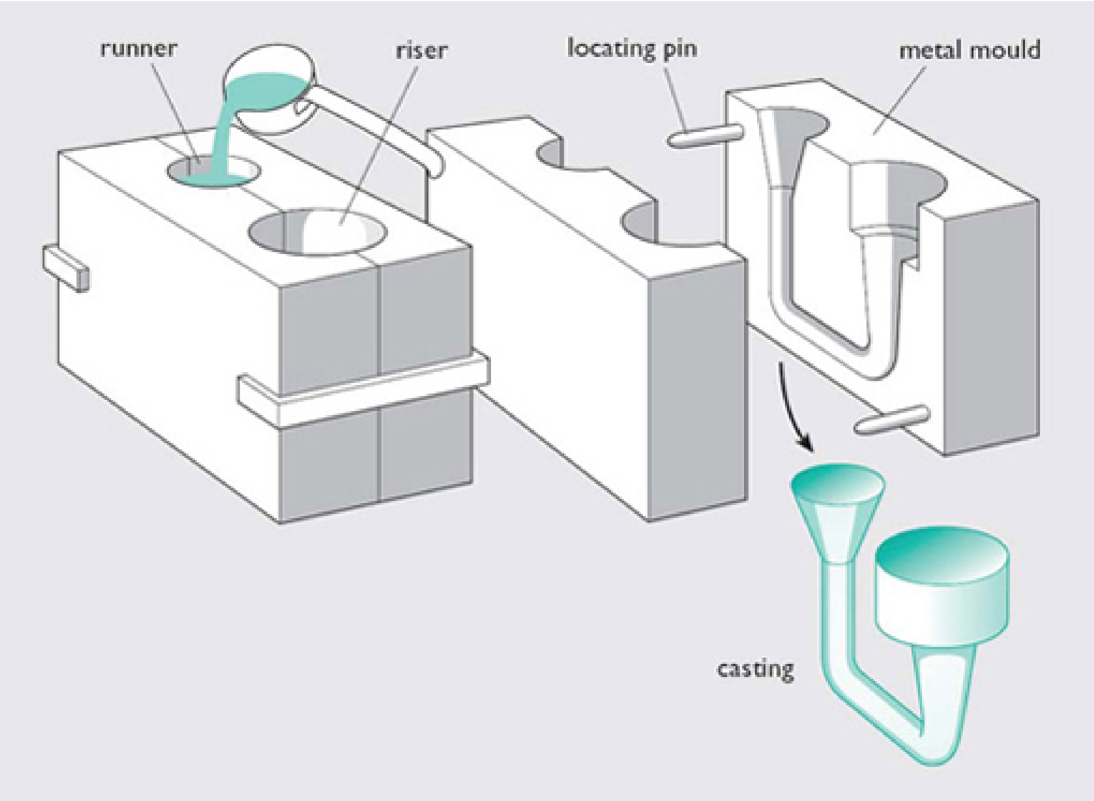


Figure 22 Gravity-die casting

Pressure-die casting, (Figure 23) is a development of gravity-die casting in which the molten metal is injected into a steel mould under pressure; it is the metal equivalent of injection moulding (which we will discuss shortly). Again, the metal being cast must have a lower melting point than the mould material. Pressure-die casting is quicker than sand- and gravity-die casting and because the fluid is under pressure, finer surface details can be replicated. It is commonly used for door handles, electric iron bases and hollow sections requiring fine detail such as carburettor bodies.

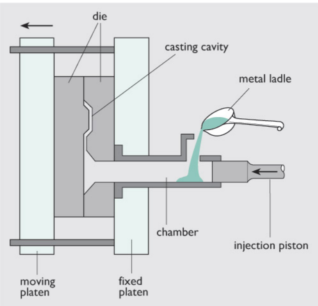


Figure 23 Pressure-die casting

2.6 Casting plastics

Injection moulding is used mainly for thermoplastic polymer materials. When heated, thermoplastics do not become as fluid as metals so they cannot be shaped by gravity-fed casting methods. The injection moulding process has been developed specifically for thermoplastics.

The process is illustrated in Figure 24, which shows the main features of an injection-moulding machine. The raw polymer, in the form of solid granules, falls under gravity from a hopper into a cylinder where it is propelled along by a rotating screw into an electrically heated section. As the material is heated, it softens and flows. When the cylinder contains enough material to fill the mould, the screw action is stopped. In the final stage, the screw moves axially, acting as a ram, injecting the material through a small nozzle, and down channels (runners) into the shaped cavity within a cooled mould. When heated, most polymers start to degrade before they reach a sufficiently high temperature to fill a mould adequately under gravity alone. Injection moulding imposes high shear flow rates on the polymer as it is squirted at high pressure into the die. This tends to align the long polymeric molecules and increase the fluidity of the polymer substantially. This shear thinning of the molten polymer is essential to injection moulding and can only be achieved if high injection pressures are used.

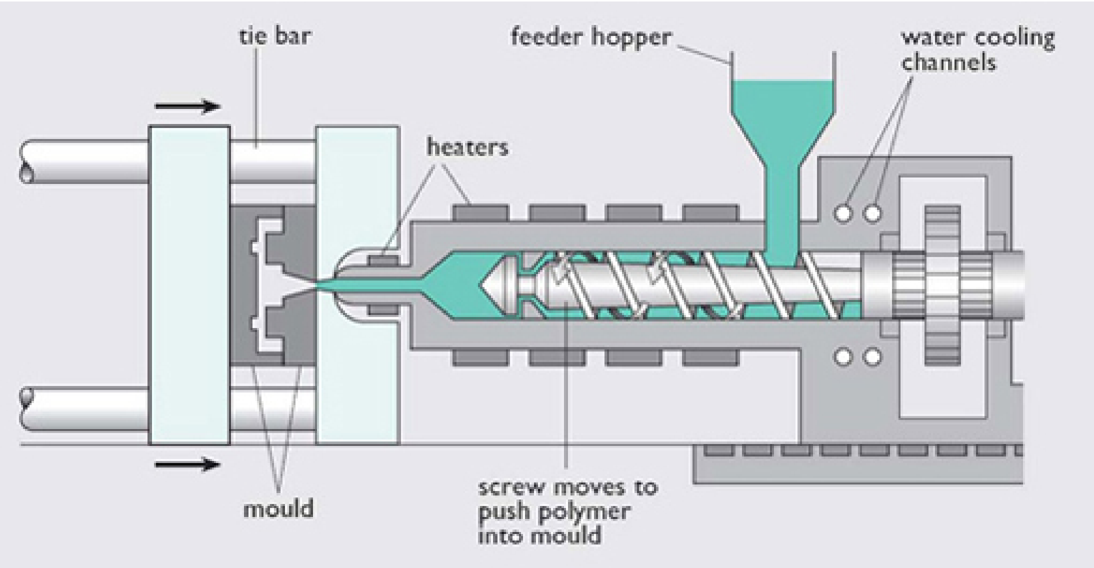
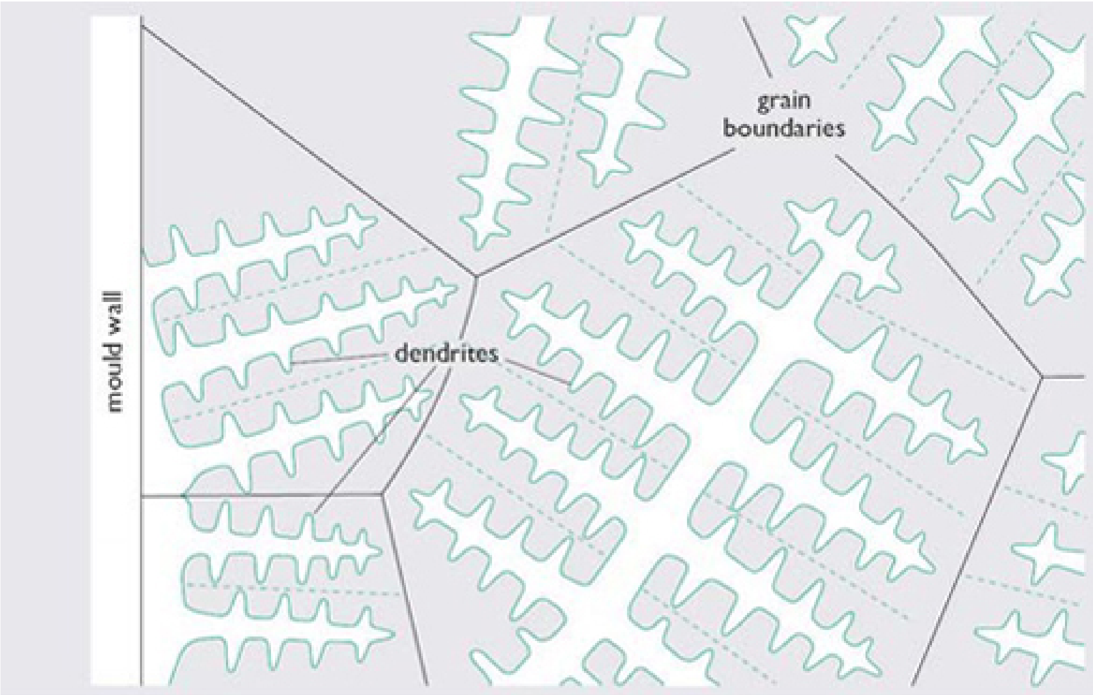


Figure 24 Injection moulding

2.7 Casting microstructure and defects

Metal castings have very specific microstructures. When a liquid metal cools and begins to solidify in a mould, grains (crystals) of the metal start to form, both on the mould walls and in the bulk of the liquid metal. The way they grow is shown schematically in Figure 25 (a). As the metal solidifies, it forms curious tree-like *dendrites* (from *dendron*: the Greek for tree). This structure is maintained after the casting is fully solidified, as can be seen from Figure 25(b), which shows a typical casting microstructure. (The image is created by polishing the surface of the metal, immersing it for a short while in a dilute acid and viewing it under an optical microscope.) In addition to the dendritic structure, there are two other common defects that can be found in a cast microstructure: particles of impurities known as *inclusions*, and *porosity* which is small holes in the casting.



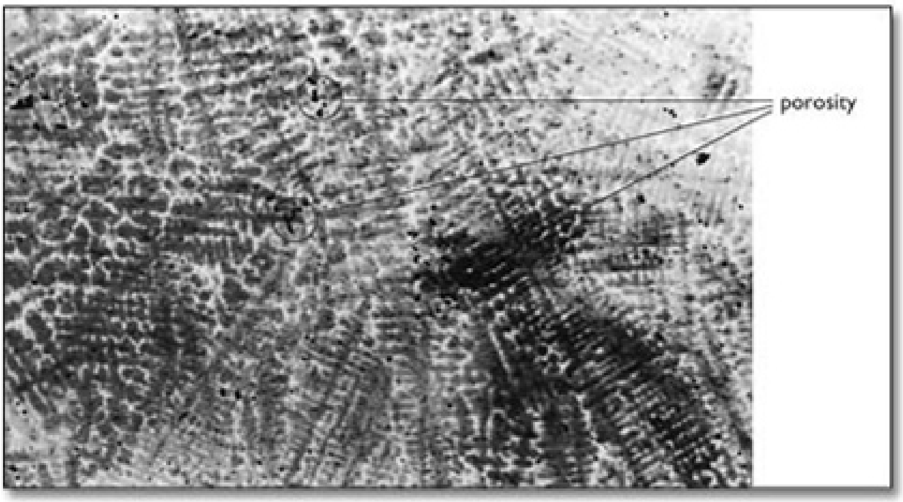


Figure 25 Castings (a) dendritic formation (b) a typical cast microstructure

Some inclusions can be removed by heating the casting to a temperature somewhat below its melting point to anneal it and 'dissolve' the inclusions in the metal; but the porosity is more difficult to remove. The porosity occurs because the casting has shrunk on solidification. Most materials contract on solidification (water is one of the few liquids that expands on solidification, so that ice floats on water; bad news for the *Titanic*, but good news for polar bears) and this shrinkage is not always uniform, so that substantial holes and voids can be left in the casting. This reduces the load-bearing capability of the component, and in highly stressed products, where the full strength of the material is being utilised, voids can lead to failure. The shrinkage on solidification can be large, and is generally a greater effect than the thermal contraction of the solid material as it cools to room temperature.

In many casting processes, runners and risers are used as reservoirs of molten metal to prevent voids from developing in the casting as it solidifies. The runners and risers are parts of the casting which contain a 'reserve' of extra liquid to feed into the mould as the cast product contracts during cooling. However, if a volume of liquid material becomes surrounded by solid material, then a void is formed when the liquid solidifies and contracts. Figure 26 shows a section through a gravity-die casting in which the effects of this contraction can clearly be seen. The chimney-like feature is the runner, down which liquid aluminium alloy was poured into the mould. There is a hollow in the top of the runner caused by liquid flowing from the runner into the mould as the casting solidified. As well as the hollow at the top, you can see some holes in the runner and one hole within the casting itself. The runners and risers will later be cut off and discarded.

Figure 26 Section though a gravity die-cast microscope body

When we are using casting to form the final shape of a product, we have to live with the microstructure of our casting, including its defects. But if we are casting ingots in order to produce sheet or bar metal for further processing, then a mixture of large deformations and high temperatures is typically used to 'break down' the cast structure, remove the porosity, and create a far more uniform microstructure. Such material is the typical raw material for the forming processes we will look at in the next section.

Polymers do not produce the same cast microstructures as are seen in metals, as they are composed of long-chain molecules, rather than grains built up from an atomic lattice of metal atoms. However, polymers do shrink on solidification and in injection-moulded products, shrinkage holes can form, particularly within thick sections. Figure 27 shows such holes in an injection-moulded nylon gear. Alternatively, the contraction may take the form of depressions on the surface ('sink marks'). In an effort to 'feed' shrinkage holes with liquid, the pressure is maintained for a short time after the thermoplastic has been injected. Similar holes are found in pressure-die castings.

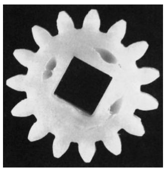


Figure 27 Section though a moulded nylon gear showing three large shrinkage holes

2.8 Casting our gearwheel

Let's now consider the problem of how best to make the food mixer gearwheel we discussed in Section 1. Could it be made by any of these casting processes? Since it is a simple solid object the answer must be yes, of course, but which processes are feasible? If the gearwheel is to be made from metal then we can consider all of the casting processes we have described:

1. sand casting;
2. gravity-die casting;
3. pressure-die casting.

Let's consider each of these in turn.

Sand casting is unattractive for volume production of this shape and size. The cast wheel would have a rough surface which would need to be machined, and a new sand mould would be needed for every product. Because the wheel is such a small component, there would be a lot of scrap, and so this makes the process rather expensive and time consuming when you need to produce of the order of 100,000 gearwheels. However, sand casting can be used for mass production of parts such as engine blocks for cars, where it is more economical than other processes. We can probably rule it out for production of the gearwheel, though!

Gravity-die casting gives a better surface finish and the die is reusable almost indefinitely. However, even this surface would need some machining in order to achieve the required accuracy of tooth shape of the gear, and to remove the runner and any little sheets of extra material ('flash') at the splits in the mould. In addition, it is a slow process, so gravity-die casting is probably not the best option.

Pressure-die casting looks promising. Here the as-cast surface needs little or no finishing, and provided the casting has the required strength for the application then this would a feasible option.

Next we consider injection moulding. Provided a thermoplastic is acceptable for the gearwheel, this process can be used. It produces an excellent surface finish (better than pressure-die casting) and has a short cycle time. Again, provided the moulding is strong enough, then injection moulding is a feasible option. So at this point in our analysis the first two candidate processes to manufacture our gearwheel are pressure-die casting and injection moulding.

3 Forming

3.1 Introduction

Forming processes involve shaping materials which are solid. As mentioned before, a simple example is moulding with Plasticene. However, metals can be moulded using forming processes as well, as long as their yield stress is not too high and enough force is used. One way to lower a metal's yield stress is to heat it up. So we can shape metals without melting them; think of the blacksmith working on a horseshoe, heated, but still solid.

However, we have identified a key quandary in forming that actually applies to materials processing in general. The properties you want from a material during processing often conflict with the material properties you require for the product in service. If you have decided that the best route to make something is to squeeze it into shape, then the properties that are required to make the product will clearly be different from the properties required when in use. For easy forming, a material needs to be soft, with a low flow (or yield) stress. These are not properties that are generally attractive or useful in finished products. More often, high strength is required; so some way must be found to make the forming of such products easier – often through the use of high temperatures (see **Properties for processing – forming**).

3.2 Properties for processing – forming

Forming processes involve applying forces to the material being shaped. A good way of telling how a given material responds to applied force is to look at diagrams representing its stress-strain behaviour. Figure 28(a) shows the stress-strain curves, at room temperature, for two different metals. The two important things for the feasibility of squeezing-type processes are the point at which the solid starts to flow and the extent to which it can be persuaded to flow before it separates (i.e. fails). This is described by two properties, *yield stress* (or *flow stress*) and *ductility*. Remember that the yield stress is a good measure of the strength of a ductile material.

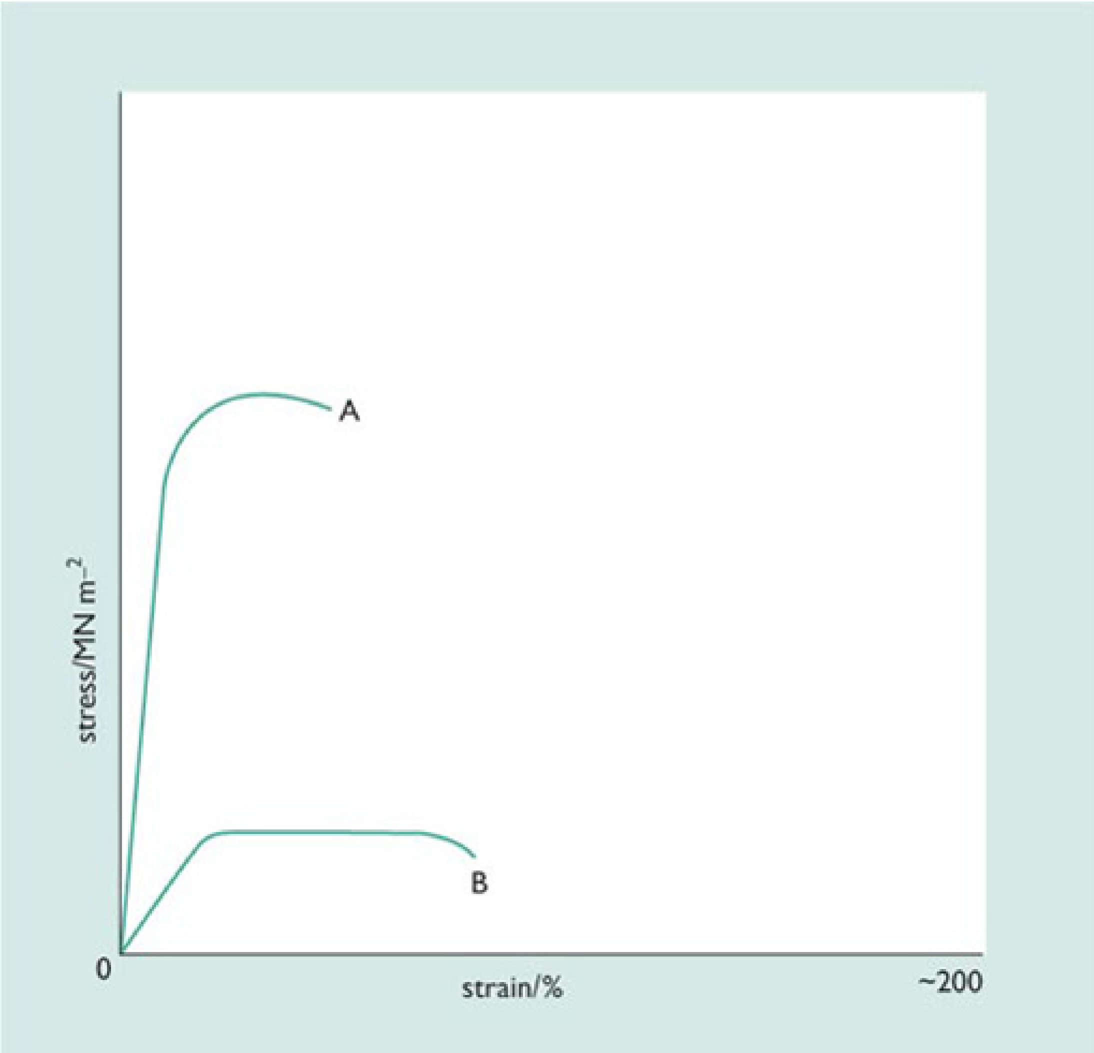


Figure 28(a) Schematic stress-strain curves for: A – a steel, B – a ductile metal such as lead

If you look at the curves, you can see that the one for the steel (curve A), after the elastic region, shows plastic deformation up to a strain of about 40 per cent. This provides a measure of the ductility of the steel, and the extent to which it can be squeezed, stretched or bent at this temperature. Curve B (for lead) shows much higher ductility and a much lower yield stress.

However, 40 per cent is not a lot of strain for many manufacturing purposes. Being able to change a material's dimensions by only 40 per cent would mean that forming would be virtually a waste of time. In addition, once the steel in Figure 28(a) has been strained plastically, it has also increased in yield stress and become harder (Figure 1.28(b)).

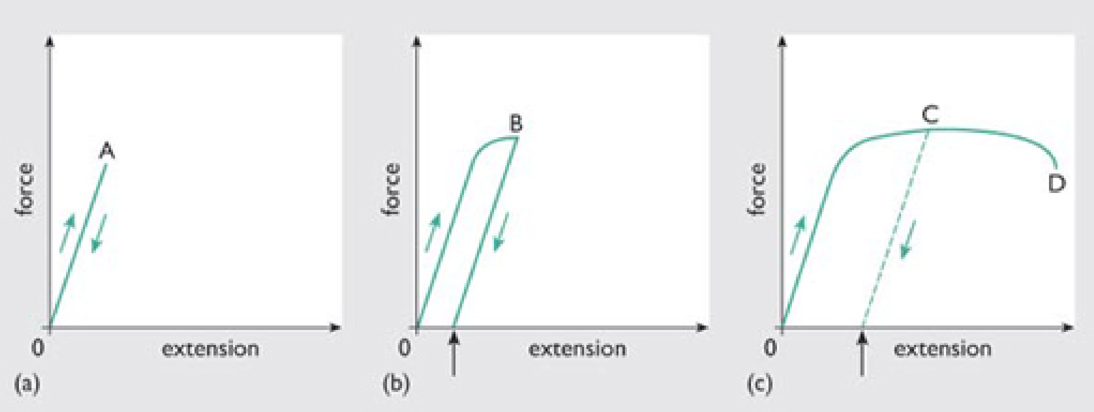


Figure 28(b) The effect of progressively straining a material

The steel can be loaded elastically up to its yield strength, point A in Figure 28(b). Removing the load below this level leaves no permanent extension, i.e. the steel can return to its original size and shape. If the material is taken above its yield strength, say to point B, then even after unloading, the steel is permanently deformed. What's more, when the material is then reloaded, it has to be loaded to a stress equal to point B – i.e. more than its original yield point at A – before it continues to flow. This is called *work hardening:* the plastic deformation causes an increase in strength (and hardness). But further plasticity is then limited. If the material is loaded to point C, where about half the available plasticity has been 'used up', then on reloading only the remaining plasticity from C to D is available before the material breaks.

However, all is not lost. The work hardening effect can be eliminated, and the original, softer, condition restored, by annealing the metal. This involves heating to a temperature where the atoms in the material become more mobile, so that the material softens. This type of process is widely applied in manufacturing whenever a part-formed product has been worked so much that it is in danger of cracking; and is why blacksmiths keep reheating a horseshoe during working. The precise mechanism of softening varies from material to material but it occurs for most materials at a high homologous temperature. Homologous temperature, T_H, is the ratio of the operating temperature of a material to its melting point (in kelvins, K).

In the context of forming, if a metal is 'hot worked', it is deformed at a temperature where there is virtually no work hardening, and this resoftening effect carries on continuously. Very high strains can be imposed during the forming process.

Conversely 'cold working' does result in work hardening, so that the material gets harder the more it is deformed. 'Cold working' does not literally mean cold, though – it is all measured relative to the homologous temperature. The rule of thumb usually employed is that cold forming occurs at homologous temperatures below 0.3 and hot forming occurs at homologous temperatures above 0.6. In between the two, there is a region known as *warm forming*. This means that if tungsten is worked at 1000°C (1273K) it is being cold formed, as its melting point is 3410°C (3683K). Conversely, at room temperature, solder can be hot worked! So working temperature is all about being able to deform the metal without failure.

3.3 Forming v casting

As the stresses needed to make solids flow are considerably higher than those required for liquids, forming processes normally require a lot of energy and strong, resilient tooling. This means high expenditure on capital equipment as well as tooling and energy. As a result, forming is often economically viable only for production volumes large enough to justify the high tooling costs.

So when do we use forming rather than casting? There are three reasons why, for many products, forming is preferable to casting.

1. Geometry. Products with one dimension significantly different in size from the others are most suitable for forming processes – 'long' products such as rails or 'thin' products such as car-body panels are usually made by a forming process. Imagine trying to cast a 50 metre length of pipe; large forces would be needed to squeeze the metal down into the mould, and it might be difficult to keep the metal liquid for long enough. There would also be a lot of scrap to discard.
2. Microstructure. As noted earlier, the microstructure of the material has a direct bearing on the properties of the final product. Controlling the microstructure is easier during forming than during casting. Also, the type of microstructures produced by forming are inherently stronger than those produced by casting, as the products of forming do not contain the dendritic structure and porosity inherent to castings. We will return to this point later.
3. Some materials are difficult to process as liquids, e.g. they may have high melting points, or react with the atmosphere.

SAQ 5

Why are car-body panels produced by forming and not casting? (*Hint:* think in terms of the shape of the final product and the form of the starting material.)

Answer

Producing thin products such as a car-body panel is very difficult by casting. To fill the mould would require the casting liquid to be very fluid and to stay that way while it filled all of the mould cavities. This is difficult to achieve. Hence it is easier to form the body panels, probably starting with a sheet of material that is pressed into shape.

3.4 Forming processes

Forming processes are used to convert cast ingots into basic product forms such as sheets, rods and plates, as was noted in the previous section. However, here we will concentrate on forming processes that produce end products or components. There are some basic shapes that lend themselves to manufacture by forming. Forming processes are particularly good at manufacturing 'linear' objects, that is, long thin ones, where the product has a *constant cross section*. Forming processes involve moving the material through an opening with the desired shape. These processes are used for making components such as fibres, wires, tubes and products such as curtain rails. The plastic ink tube in your ballpoint pen was almost certainly produced by this method.

3.5 Extrusion

The principle of this process is very similar to squeezing toothpaste from a tube. Material is forced through a shaped hollow die in such a way that it is plastically deformed and takes up the shape of the die. The hole in the die can have almost any shape, so if the die is circular, for example, a wire or rod is produced (Figure 29).

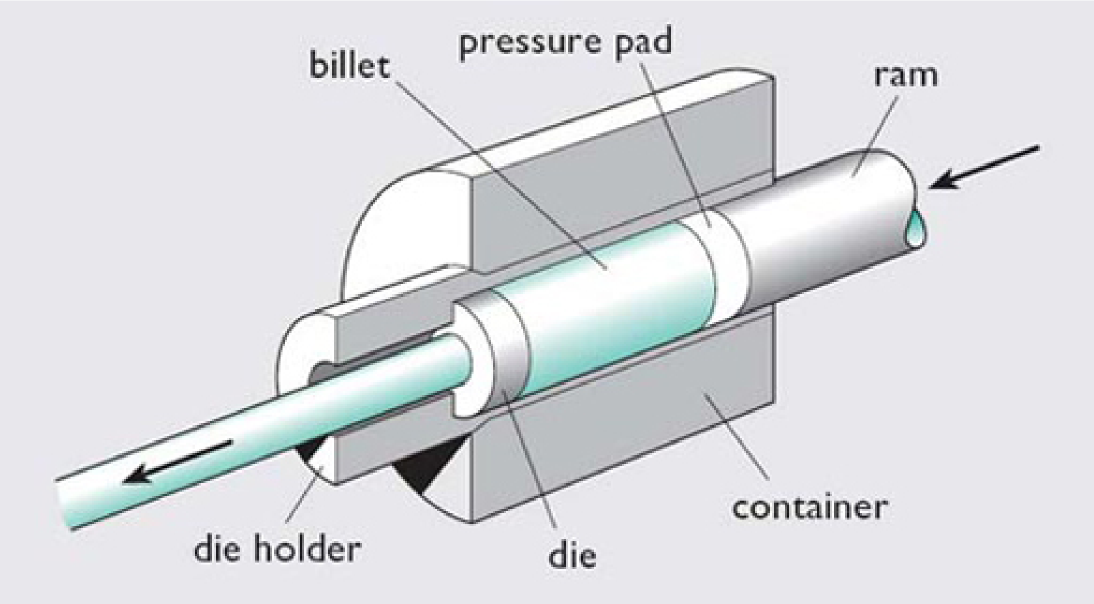


Figure 29 Metal extrusion

It is also possible to produce hollow sections using extrusion. In this case, the die contains a short piece (or mandrel) in the shape of the hole. This mandrel is attached to the die by one or more 'bridges'. As the extruded material encounters the bridges it is forced to separate, but it flows around the bridges and joins up again, much the same as water flowing around the piers of a bridge. Figure 30 shows such a 'bridge die'. This works successfully even for processing of solid metals.

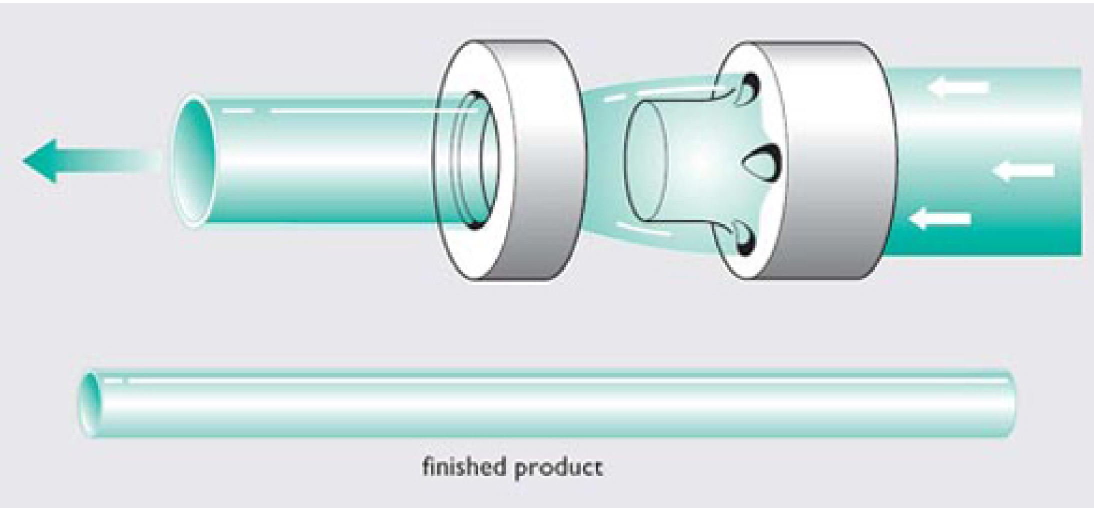


Figure 30 Extrusion bridge die making a hollow section product. Note that in the picture the die has been split to show the material passing through it. In reality, the die and the ring fit together, with a gap for the extruded material to flow through

Extrusion can be used on most materials that can plastically flow as a solid, and solid metals and alloys are frequently extruded. To reduce the stresses required, and therefore the size and cost of the extrusion machine, and also to ensure hot working conditions, a metal is usually extruded at a high homologous temperature, usually between 0.65 and 0.9. This allows large changes in the shape of the material – and hence large strains – without fracture. During metal extrusion the raw material in the form of a metal ingot, known as the *billet*, is heated and pushed through the die by a simple sliding piston or *ram*.

The mechanism for extruding thermoplastics is illustrated in Figure 31. In this case a rotating screw is used to transfer the raw material in the form of granules through a heated cylinder to the die, just like in the case of injection moulding for polymers. The thermoplastic granules are compressed and mixed by the screw (the granules may contain a second constituent such as colouring). The material softens and melts as the temperature rises due to heating through the walls of the cylinder, and also from the heat generated within the thermoplastic as it is sheared by the screw. The thermoplastic flows through the die and emerges with a constant cross section in the shape of the die aperture. An almost infinite variety of cross-sectional shapes can be produced.

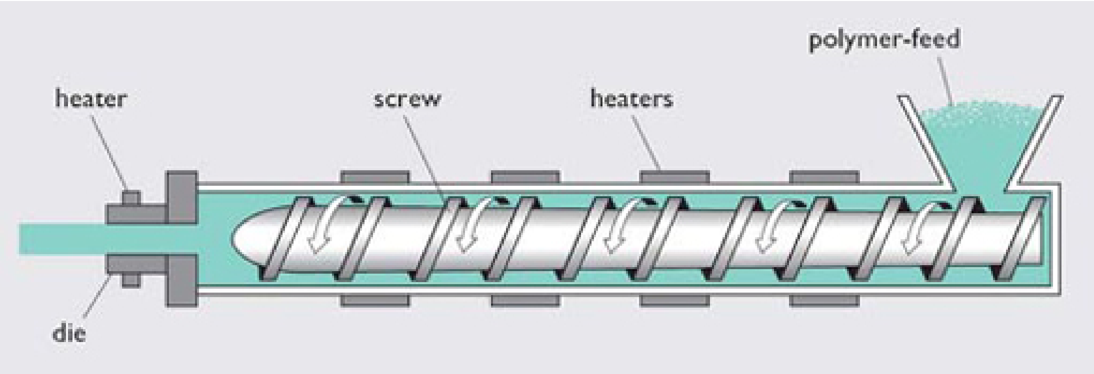


Figure 31 Thermoplastics extrusion

SAQ 6

Could extrusion be used for the following products?

1. The body of a food mixer.
2. Copper pipe for a central heating system.
3. The body of a pen.

Answer

1. The body of the food mixer has a complex 3D shape, so it certainly could not be extruded.
2. Copper pipe is ideal for manufacturing by extrusion, using a bridge die to extrude the hollow shape.
3. The ink tube in the pen has probably been extruded. But the bodies, even the cheaper ones, vary in diameter along their length and are typically closed off at one end. This would suggest that the pen body is not extruded.

3.6 Rolling

In rolling (Figure 32), material is passed through the gap between two rotating rollers that squeeze the material as it passes between them. The rolled material emerges with a thickness roughly equal to the gap between the rollers. When the rollers are cylindrical, rolling produces material in the form of plate or sheet. Sheet steel and aluminium for the bodies of cars and domestic appliances is made this way. Rolled sheet is often termed a 'semifinished' product, as it requires further processing to shape it into the final product.

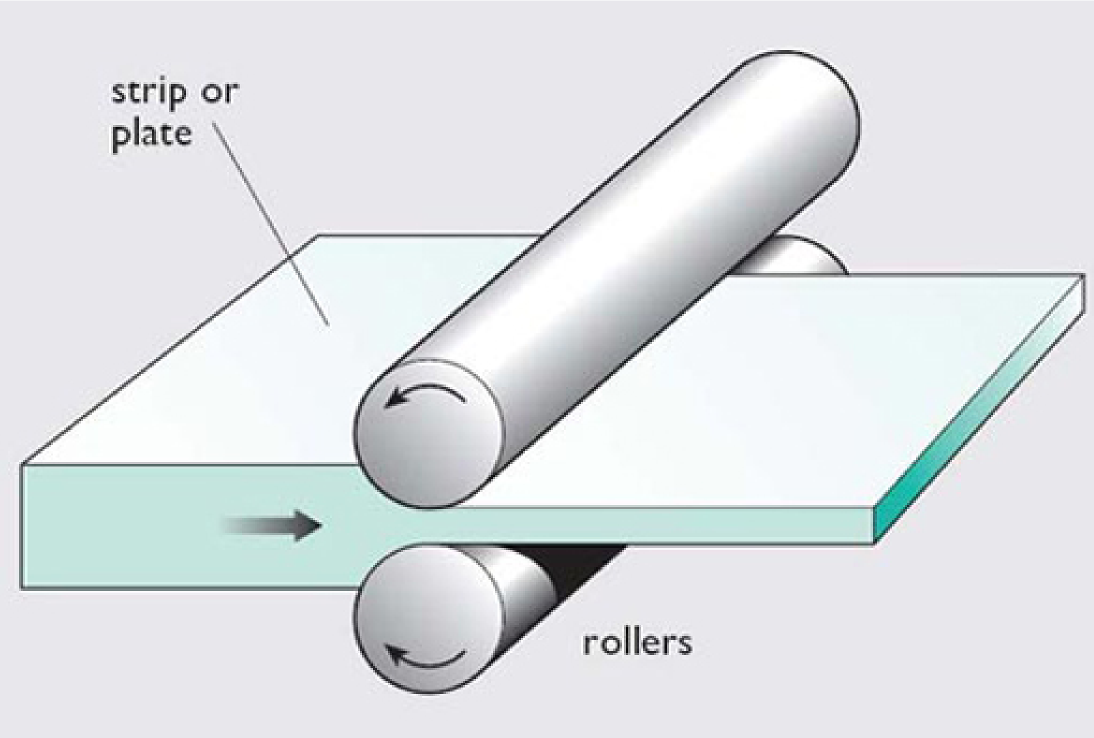


Figure 32 Rolling

Rolling is not restricted to flat sheets, though. If the desired product has a contoured surface, then by using profiled rollers the contour can be rolled on. If the surface pattern needs to be deeper than is possible during one rolling pass then multiple rollers can be used; for example, railway tracks are made by rolling between pairs of progressively deeper contoured rollers. The various stages for rails are shown in Figure 33.

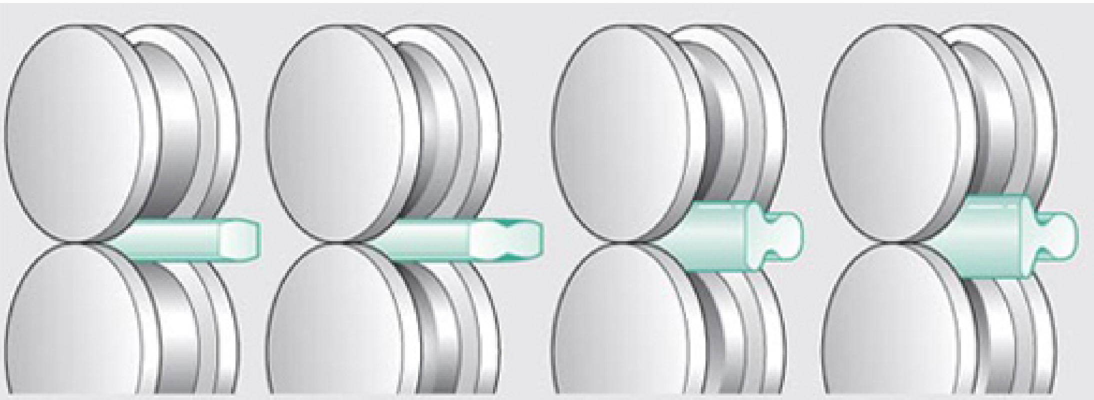


Figure 33 Stages in rolling railway track

In common with other forming processes, metals may be hot or cold rolled. The significant differences between hot and cold rolling are in the amount of energy needed to roll a given volume of material and in the resulting microstructures. The cooler the metal, the higher its yield stress and the more energy has to be supplied in order to shape it. As in extrusion, metals in large lumps are often hot rolled at homologous temperatures above 0.6. At this temperature the yield stress and work hardening are reduced. Railway lines require hot rolling in order to achieve the large change in shape from a rectangular bar. However, a major disadvantage of hot rolling is that the surface of the material becomes oxidised by the air, resulting in a poor surface finish.

If the metal is ductile then it may be cold rolled using smaller strains. This has some advantages: the work hardening at these temperatures can give the product a useful increase in strength. During cold rolling, oxidation is reduced and a good surface finish can be produced by using polished rollers. So, cold rolling is a good finishing treatment in the production of plate and sheet. The sheets of steel for car bodies are finished by cold rolling because a good surface finish is essential in this product.

3.7 Metal forging

Forging is typified by countless generations of blacksmiths with their hammers and anvils. Besides still being used for special 'hand-made' items, this type of forging is similar to that used, on a somewhat larger scale, for the initial rough shaping of hot metal ingots. Forging is particularly good at making 3D solid shapes. The basic types of forging processes are shown in Figure 34.

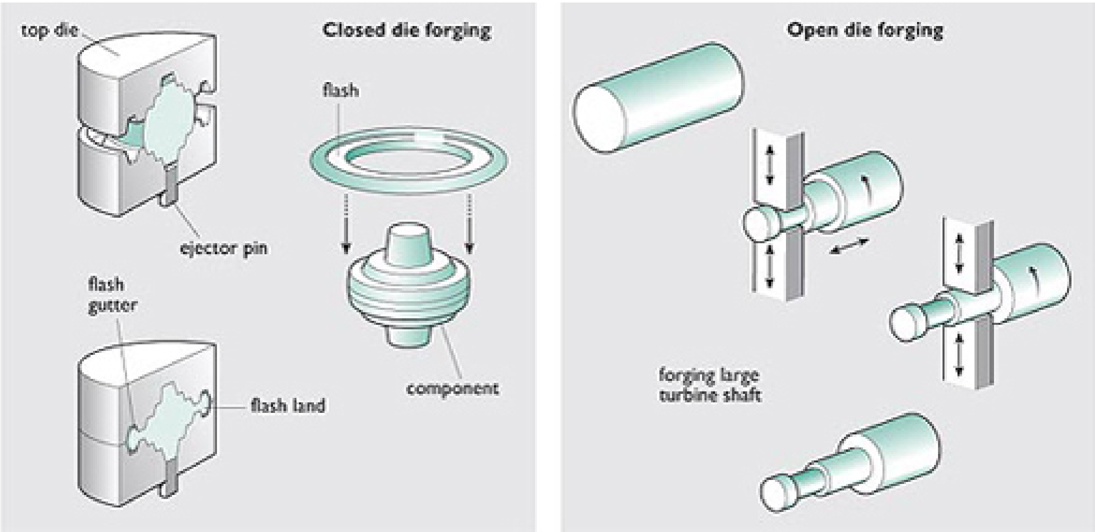


Figure 34 Forging processes

For example, the first stage in making a large roller or shaft would be to forge a large billet as sketched in Figure 34. The process consists of a large succession of bites between a pair of dies in an hydraulic press, with the ingot moved between each bite. As the ingot is moved through the dies it is reduced to a more manageable size before final shaping – this process is known as *open die forging*.

In *closed die forging* components are made in one action, being squeezed between upper and lower shaped dies as shown in Figure 34. There is usually a small amount of excess material which is forced out of the die cavity as *flash*. This must then be removed from the component. The force needed to close the dies together is dependent both on the size of the component and the temperature, since as we noted earlier, the flow stress reduces as the forging temperature increases. The quality of the surface finish of the forging decreases with temperature, however, because of increased surface oxidation.

3.8 Forming our gearwheel

We have just seen that simple 2D 'linear' objects can be produced by rolling, drawing or extrusion. So could our gearwheel be made using these techniques?

Because the gearwheel has a constant section it is geometrically feasible (actually the section is not quite constant because it is countersunk on one side, but let's ignore this fine detail for the purpose of this discussion). Drawing is confined to small reductions in cross-sectional area during each pass, so this process does not look promising, but there is no such limit on extrusion. By extruding a deformable material such as metal or thermoplastic through a bridge die containing a gear-shaped hole and a square bridge it should be possible to produce a very 'thick' (or long, depending on how you want to describe it!) gearwheel (see Figure 35). This can then be cut up into identical gearwheels of the required thickness, so this might be a possibility.

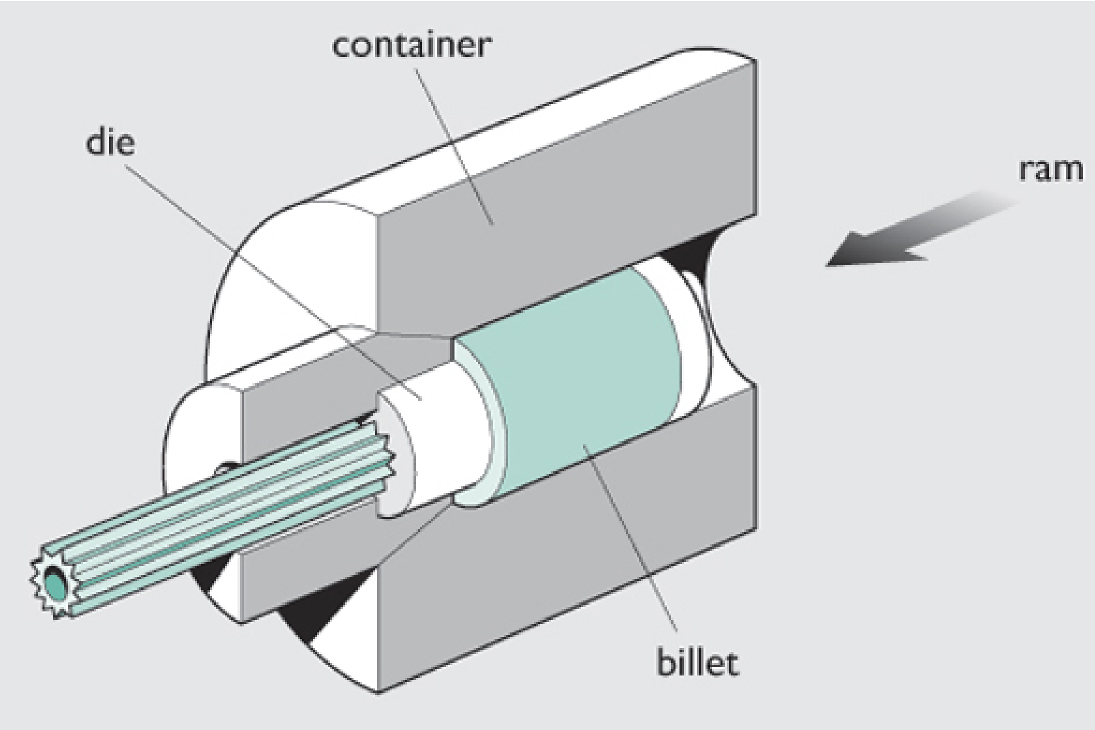


Figure 35 Extruding a gearwheel

Would rolling be an alternative manufacturing process? It would be difficult to roll the gear teeth profile, but you could use rolled steel sheet as a starting material. You could then punch out a gear-shaped blank using sheet metal forming (Figure 36). This would be expensive, but is possible.

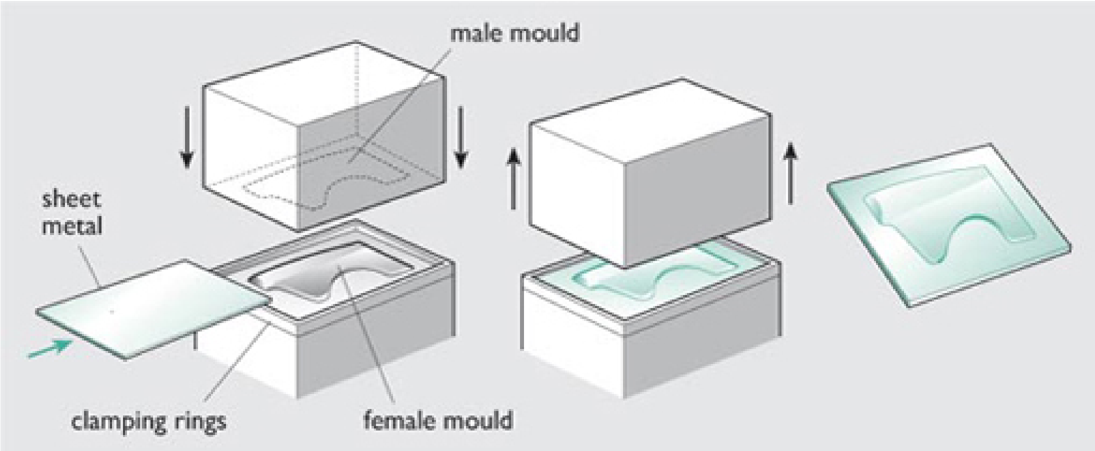


Figure 36 Sheet metal forming of a car body panel

However both extrusion and the sheet-metal route would produce flow lines not suitable for an engineering gear, as described in **Failure of replacement gears**.

So let's go back to our gearwheel again and decide whether a gearwheel can be made by forging. The answer is yes, but only partly. Some other processing would be needed either before or after the forging process.

One approach is to start with steel bar (itself produced by rolling between contoured rolls). The bar contains longitudinal flow lines in its microstructure, produced from the rolling operation. This bar is forged into a circular, gear-sized, disc by compressing the bar parallel to its length (Figure 37).

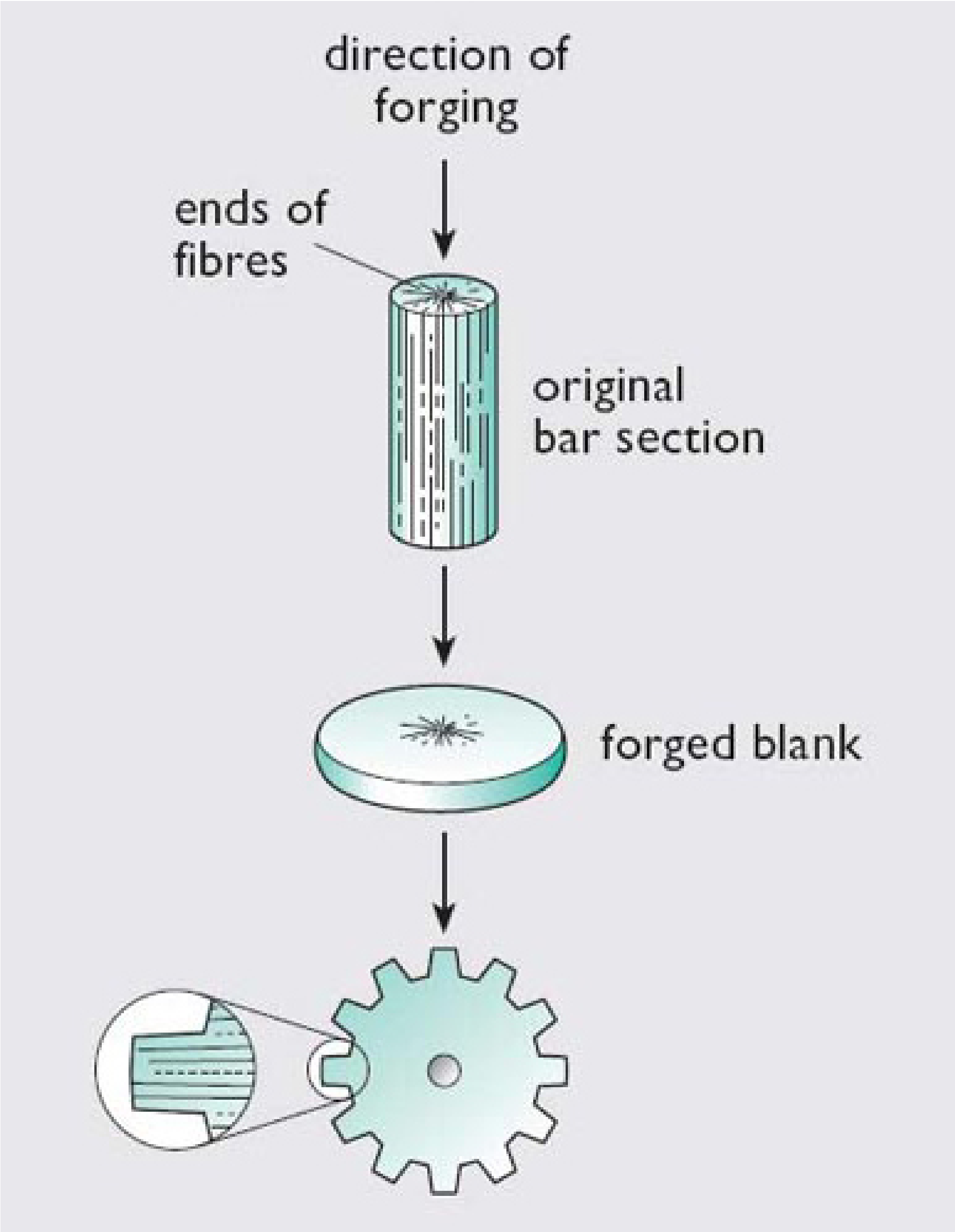


Figure 37 Forging a gear

The forging 'folds over' the longitudinal flow lines into the radial direction. So in this case, *all* the gear teeth have the optimum orientation of flow lines and the final product is stronger than that made from rolling. **Failure of replacement gears** describes why the microstructure of gears can be of critical important to their performance.

SAQ 7

Which of the processes (including both casting and forming) covered so far would be the most appropriate to manufacture the following products? Use the shape hierarchy for both casting and forming to help guide you through some of the options.

1. A church bell.

2. Aluminium foil for food use.
3. A plastic beaker.
4. The plastic body of a food mixer.
5. Copper pipe for use in plumbing.
6. A shaft for use in a car engine. (*Hint:* the component is manufactured from solid steel. The shaft requires high strength for this application. Think about its shape – I would classify it as non-complex.)

Answer

1. Whilst it might be possible to forge a bell, the tooling would be very costly for a one-off, so sand casting is the best option here.
2. A sheet-like shape such as this would be made by rolling, using progressive reductions in the sheet thickness.
3. A plastic beaker could be made by injection moulding.
4. If the body is to be made of plastic then injection moulding would be the only choice. This is a process which can produce complex 3D shapes.
5. The pipe is a simple 2D shape, so could be made by extrusion using a bridge die.
6. For high strength, forging is better than casting. As the component is solid and the shape is non-complex, closed-die forging would be used.

3.9 Failure of replacement gears

A heavy commercial vehicle company announced that it would no longer supply spare parts for one of its vehicles. This was a problem for customers, as the two largest gears in the gearbox tended to wear faster than the others and it became impossible to replace them even when the other parts still had a great deal of useful life. A specialist firm set out to manufacture spare parts and soon had orders for dozens of sets of these two particular gears.

This firm had measured the gears and manufactured new ones of identical dimensions, using one of the strongest steels available. It machined the gears and sent them out for heat treatment as, in addition to hardening and tempering the whole gear, the teeth had to be surface hardened to match the hardness of the originals.

All seemed to be well until a pair of gears was returned, having failed by teeth breaking off in just over three weeks' service. The failure was assumed to be due to poor driving. So another pair was put in the gearbox, but a similar failure occurred in less than one week.

The problem was then easily identified by comparing the new gears to the originals.

The gears were made of steel that started off as cast billets. In the as-cast state, the steel has no directionality to its microstructure but, as it is worked down to billet or bar, directionality appears as grains and inclusions are extended in the direction of working. The directionality is revealed as 'flow lines' which resemble the grain in timber. For any given quality of steel, the strength is much better across the flow lines than in parallel with them).

Figure 38 is a view of the gear showing the inner upper ring of teeth which were breaking off. A radial section was cut from the original gear and a similar one from an unused new gear. These were polished and the flow lines revealed by etching. Figure 39 shows the old gear at the left and the new gear at the right. The teeth which were breaking off were the small ones which are at the top in the sections of Figure 38. In the old gear they are worn down, which is why the gears needed replacing. The unused new gear shows the teeth in side profile. The section has been cut so as to include the full section of the large teeth around the outside.

Figure 38 An unused gear (on the right) showing the ring of teeth which were breaking off – the smaller teeth at the top of the gear. The gear on the left was a used gear where the teeth have been worn away.

Figure 39 Sections etched to reveal flow lines: (left) original gear, inner teeth worn now; (right) new gear, inner teeth full profile. The teeth are on the bottom left of the cross-sections – compare the sections to the cuts in Figure 38.

What difference is there in the flow lines in these two sections?

In the new gear they all run parallel to the axis and, if this were made of wood you would expect them to break off easily. In the old gear the flow lines are in a looped, radial pattern tending to run at right angles to the gear's axis. If you look carefully at the small teeth you will see that they run pretty well at right angles to the direction of the flow lines in the new gear.

The original gears had been forged before the teeth were cut, whereas the replacements had been machined directly from round bar. The flow lines tell us that the old gears had started off as a length of round bar about twice as long as the gear is thick, but of smaller diameter. This was hot forged to squash it down, causing the outside to spread out so that the shape finished up with a much larger diameter and shorter length than when it started. This was done specifically to develop the flow line pattern you can observe. When the teeth were cut, the grain flow was oriented at right angles to the applied bending stresses in service. The teeth were thus as tough as they could be for this type of steel and the flow lines were oriented in directions which imparted the maximum resistance to failure.

In contrast, the new gears had been machined from stock of the full diameter the gear required. There was no forging, so the flow lines remained parallel to the gear axis.

The result was that the flow lines in the teeth were in the most unfavourable orientation to resist fatigue and brittle fracture. This is why they broke off so quickly under service loads, despite having the same hardness (and tensile strength) as the original gears.

SAQ 8

1. Which of the processes covered so far could be used for making the cap and body for a ballpoint pen? Start by classifying their shapes.
2. On cheap versions of such pens, there are often thin lines running the length of the body and/or the cap. What do you think is the origin of these lines?

Answer

1. Both of these are non-continuous 3D hollow items, so injection moulding would be used.
2. The lines are 'flash' from the join between the two mould surfaces; more expensive pens will have had the lines polished off after moulding.

3.10 Powder processing techniques

Before we leave forming we should consider powder processing techniques, (Figure 40), which have elements of both casting and forming. Essentially all powder processing routes involve filling a mould with powder (this is similar to filling the mould during casting, as powders flow as slurries), which is then compressed in between dies to begin the process of reducing the space between the powder particles. The powder compact produced is then heated to a high temperature to produce a solid component.

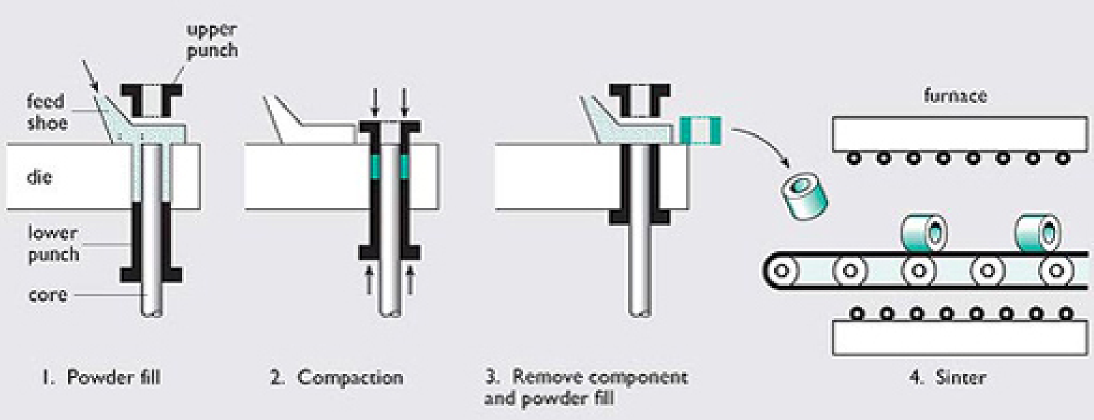


Figure 40 Powder processing

The process of sintering starts with the material in powder form and is used for a wide variety of materials, especially those with properties which preclude shaping by melting and casting. Examples are ceramics such as alumina and silicon nitride; brittle metals with high melting temperatures (over 2300K), such as tungsten; and the polymer PTFE (polytetrafluoroethylene), which has a viscosity too high to suit other moulding methods.

The starting powder is mixed with a lubricant/binder and is then moulded to shape by compressing it in a die to form what is called a 'green' compact. Although this is highly porous, it has enough rigidity to support its own weight and permit gentle handling. The compact is then sintered – that is, heated at a high temperature and sometimes under pressure – for a prolonged time. During sintering, the powder particles coalesce (small particles join together to form larger ones) and grow to fill the pore spaces. The compact shrinks correspondingly, forming a solid homogeneous (uniform) mass in the shape of the original mould. Depending on the sintering process used, the final component can have various degrees of porosity and therefore strength, as any porosity can act as defects in the form of cracks. Very high temperatures and/or pressures during sintering are used to minimise porosity.

In powder processing, the volume of the workpiece does not stay constant. As the powder fuses together, most of the spaces between the powder disappear and the volume of the finished component is considerably reduced.

Sintering is sometimes economically competitive with alternative methods of shaping; for volume production of complex parts it is often cheaper than machining. A wide variety of components can be manufactured using powder processing: these can range from processing domestic ceramics for applications such as bathroom sinks to the insulating sleeve in a spark plug.

So can we consider production of the gearwheel using powder processing? As you have seen powders of many materials can be used for this process and this includes metals. This would appear to be an attractive idea because the wheel can be made in one piece, with little or no waste of material and with a modest expenditure of energy and labour. The only major problem is the need for a shaped punch and die. This is expensive, but if the price of the punch and die can be spread over a long production run, the cost of the product may be quite reasonable. So as well as extrusion and forging, which we identified earlier, we can add powder processing to our list of candidate processes to make our gearwheel.

4 Cutting

4.1 Introduction

Cutting is perhaps the most familiar type of manufacturing process. Whilst few of us have cast polymers or formed metal, shaping material by cutting is part of everyday experience. I am sure you have used scissors, saws, files, chisels or even sandpaper at some time in order to remove unwanted material. These are all mechanical methods where a force is applied through the cutting tool (whether it is the grit in sandpaper or the metal edge of a saw) to the material, and a cut is made on a macroscopic or microscopic scale.

Cutting is often used as a secondary or finishing process where the product to be cut will have been made by one of the processes described earlier. On a similar basis, if you do any DIY at home using wood then you will purchase ready prepared timber as a starting point rather than manufacturing it from the raw material, in this case trees. You may have to cut the timber to size to do a particular job, but a number of previous processes will have produced material of suitable dimensions, saving time and a lot of hard labour.

There are a number of reasons for using cutting as a secondary manufacturing operation in the production of a particular artefact:

- to improve dimensional accuracy;
- to improve the surface finish;
- to produce geometrical features such as holes and slots, which are difficult to produce in the primary manufacturing process.

Indeed, the majority of components produced by forming and casting require some subsequent material removal before reaching service.

However, in some circumstances it can be more economical to produce the basic product shape by cutting from solid rod or plate (although some form of shaping will have been used to manufacture even these basic starting shapes), than by any other process. As cutting typically uses machines with little dedicated tooling, this is particularly true for low production runs.

If the material costs for the product are low, then the waste from cutting will constitute only a minor part of the overall cost. The inherently poor material utilisation of cutting processes can be tolerated and automation can make cutting attractive at much higher production volumes. Cutting can then compete directly with casting and forming for the manufacture of some products.

Exercise 3

1. What advantages are gained by using cutting as a finishing process?
2. When might it be reasonable to use cutting as a primary manufacturing operation?

1. Cutting gives good dimensional accuracy and a good surface finish. It can also be used to produce holes etc., that would otherwise be difficult to introduce into the product.

2. Cutting is a feasible manufacturing operation for small runs, where the cost of tooling is relatively low, or if waste generation is not expensive.

4.2 Cutting processes

The most common cutting operations are carried out on electrically-driven machine tools; hand tools, which include electric drills, orbital sanders and the like, are also used extensively, but because of the limited number of items that can be produced economically it is not a viable manufacturing method for mass production. In industry, cutting was traditionally performed on large machines with a whole host of specialist names such as lathes, mills, broachers, shapers and many others. Each type of machine was capable of one particular method of cutting. Somewhat confusingly, these cutting machines are collectively known as *machine tools* and the processes are known as *machining*. The skilled operators of these machine tools had a significant influence on both engineering practice and labour relations for many years. However, the last few decades have seen substantial growth in the use of flexible, computer controlled *machining centres* (Figure 41) that incorporate both tool- and workpiece-changing facilities. The introduction of such machines, together with their reduced need for a skilled workforce to operate them, have reduced operating costs so that cutting can now be considered for production volumes that would previously be considered uneconomic.

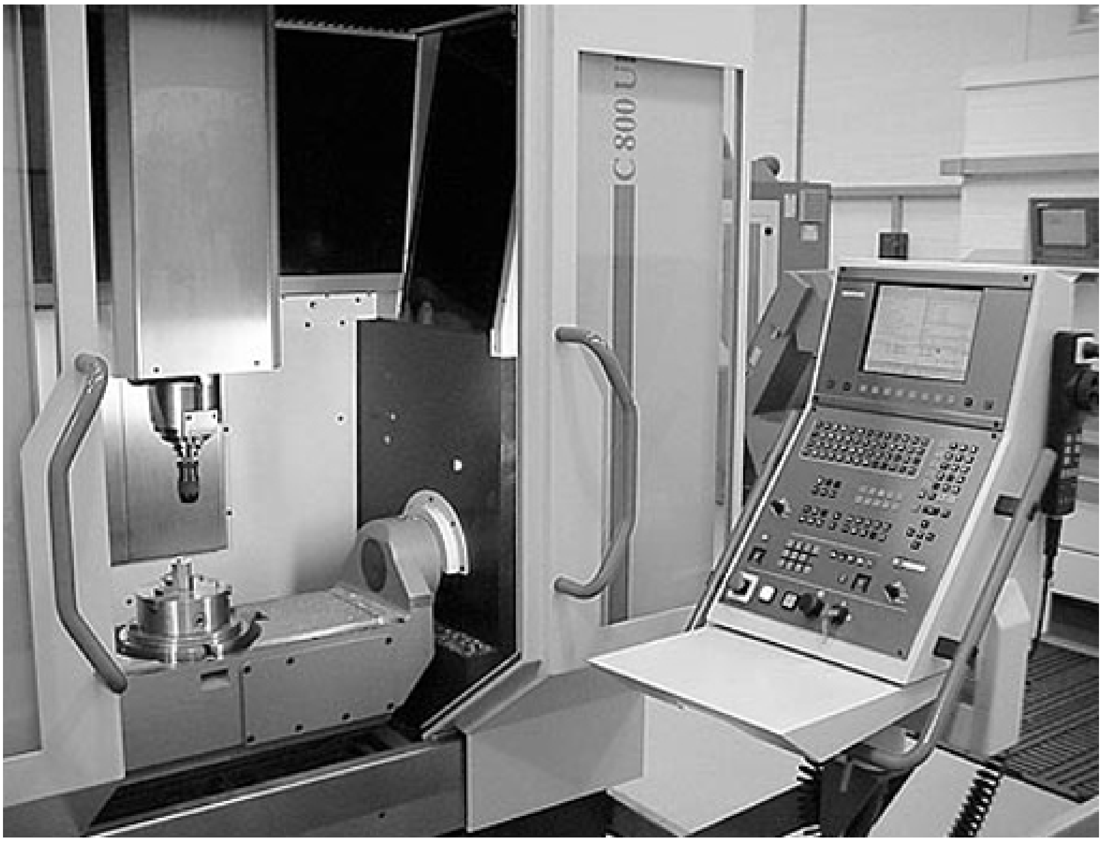


Figure 41 Typical computer-controlled machining centre

4.3 The mechanics of machining

During any machining operation, the cutting tool comes in contact with the material to be cut, called the workpiece. The cutting machine has to hold both the tool and workpiece, and to move one relative to the other for the cutting operation to be performed.

All cutting processes are essentially complex arrangements of a simple single-point cutting operation: a saw blade is just a collection of single-point cutting tools; sandpaper is lots of single-point cutting grits stuck onto a piece of paper.

When the cutting tool is brought into contact with the workpiece, it detaches a thin layer of unwanted material (the 'chip'). Figure 42 shows the relative position of tool and workpiece during a machining operation. The tip of the tool is shaped like a wedge so that the faces of the tool are always inclined to the machined surface of the workpiece in order to limit the area of rubbing between tool and workpiece. This rubbing is undesirable because it wastes energy and it causes the tool to wear at an increased rate.

Figure 42 Chip formation during machining

In deforming the chip, work is done by the tool on the workpiece and more than 90 per cent of this energy is transformed into heat. This heat is concentrated in a small volume of the workpiece near the tip of the tool. The actual temperature profile near the cutting point depends on the thermal and mechanical properties of both the tool and workpiece but it is common for temperatures to reach 700°C locally, even when liquid coolants are used.

At these temperatures, a state of partial seizure or bonding exists at the tool/workpiece interface, as the chip starts to weld to the tool. This is highly undesirable, since it contributes both to wear of the tool and to the consumption of energy during machining. Lubrication does help relieve the situation, but the careful design of the cutting tool is of paramount importance. There are specific tool geometries and cutting angles for different materials which help to keep temperatures and energies to a minimum while they are being cut.

The main attraction of machining as a shaping process is its ability to produce almost any shape accurately. However, machining requires expensive capital equipment and can also produce a lot of waste material, and for large production volumes it often proves more expensive than alternative methods of shaping.

As we see from the above, there are two materials involved in machining: one is the tool and the other the workpiece. During machining, the material of the workpiece should deform plastically (or 'flow') while that of the tool remains rigid. So the tool material must be much harder (measured in terms of **Hardness**) and stronger than the workpiece at the temperatures that exist near the tip of the tool. Also, the tool should be stable at the cutting temperature; it should not oxidise or undergo microstructural changes which may decrease the strength of the tool. Wear of the tool is inevitable under machining conditions, but by using material that has a high wear resistance, tool life is maximised.

4.4 Hardness

Hardness is related to the strength of a material and is a measure of a material's resistance to plastic deformation by scratching or indentation. Scratching the point of a pin across a material can be used to give a rough indication of hardness, but this is purely qualitative as it indicates only whether the material is harder or softer than the pin.

Hardness is one of the oldest ways of comparing the properties of materials. German mineralogist Friedrich Moh originally developed a scale for minerals which ran from 1 to 10 based on which would scratch each other. On this scale, diamond, the hardest, ranked 10 and talc, the softest, ranked 1, with other minerals in between. This scale is sometimes still used but its drawback is that the steps in between the different minerals are too large to be useful to discriminate between similar materials and the steps are not equal.

Thus, a range of other techniques to measure hardness have been developed. Some of these are based on pressing an indenter of a known geometry, such as a hardened steel ball or a pyramid, into a surface under a known load and then measuring the size of the residual impression. One of the more popular methods for both metals and plastics is the Vickers hardness test (Figure 43). This test uses a pyramid-shaped diamond to indent the surface, the size of the indent being related to the hardness; the softer the material the larger the indentation. The Vickers hardness number, HV, is the force divided by the surface area of the indentation. The values of HV for a range of materials are shown in the appendix.

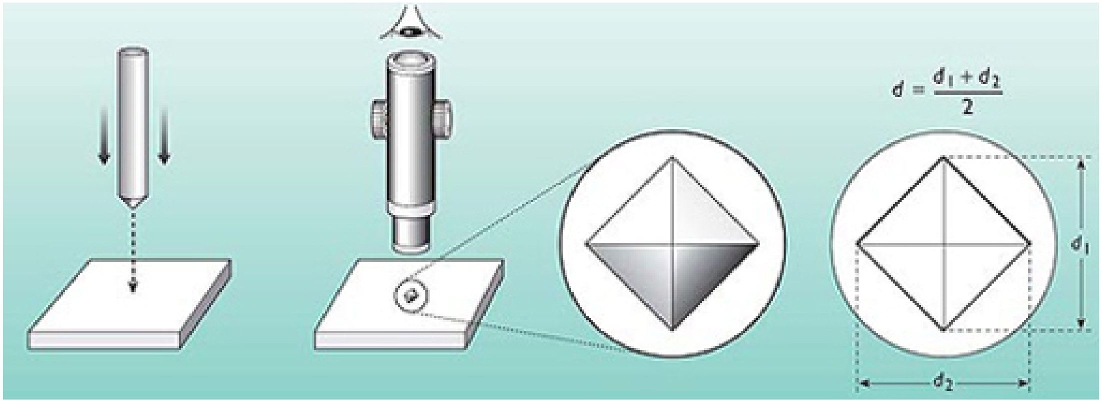


Figure 43 The Vickers hardness test

4.5 Types of tool material

There are basically three types of tool material:

- tool steels;
- metal carbides;
- ceramics, including diamond-like materials.

Tool steels have been available since the turn of the nineteenth century, and are still the mainstay of tool materials. They are alloys of iron and carbon with additions of elements such as chromium, tungsten, molybdenum, titanium and vanadium. These elements improve the cutting properties of the steel and the response to heat treatment.

Metal carbide tools, which are also often called *hard metal* tools, are made by mixing together powders of cobalt (chemical symbol Co) and a metal carbide (usually tungsten carbide, WC). These are then sintered using powder processing techniques. The particles of carbide (which are hard and very strong, even at machining temperatures) form the cutting surfaces of the tool and the function of the cobalt is simply to hold together all the carbide particles. You can see from Figure 44 that the microstructure consists of particles of metal carbide, embedded in cobalt. This is a good example of how physically mixing two materials having differing property profiles can produce a *composite material* which has more useful properties than either of its constituents.

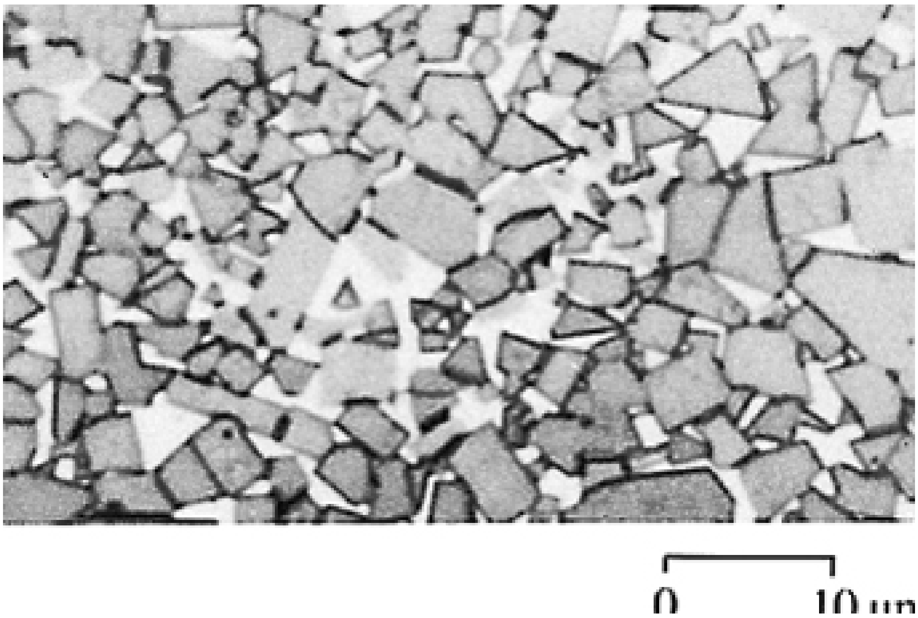


Figure 44 Microstructure of a WC/Co hard metal tool

Finally, *ceramic* tools usually consist of aluminium oxide (Al_2O_3), sometimes with small additions of magnesium oxide (MgO). They are also made from blended powders using the sintering process. These tools retain good strength and chemical stability at high temperatures. More specialist tools can also be made from ceramic composite materials (by mixing two or more ceramic materials) and also diamond, which is used for machining non-ferrous and very hard materials.

These ceramic materials are also used as the tooling in grinding processes. These use a high-speed rotating wheel made of a porous abrasive material which removes a small layer of material as it passes across the workpiece (Figure 45). In this case there are many thousands of small cutting edges where the hard abrasive particles, such as diamond or aluminium oxide, protrude from the surface of the wheel. Grinding is used to make surfaces (usually flat or cylindrical) with a good finish on hard materials, as the size of cut and therefore the chip is very small. As the amount of material removed during grinding is minor, grinding is normally considered as a finishing process.

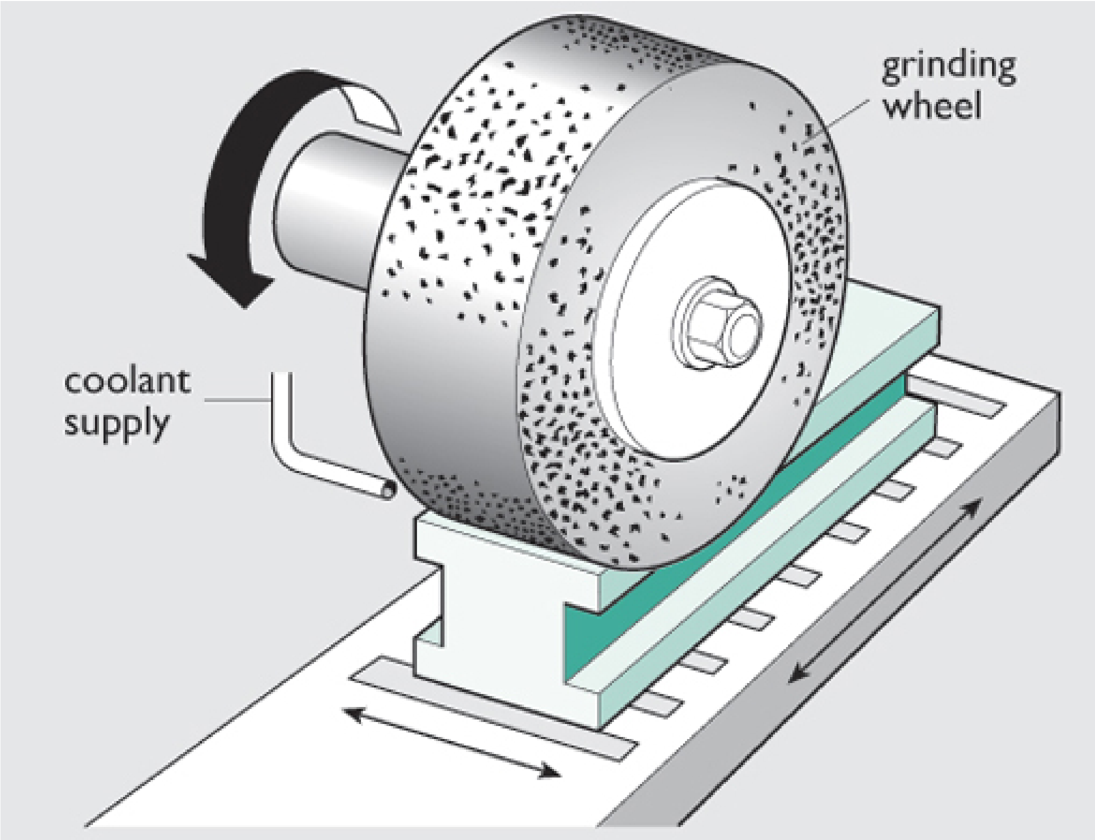


Figure 45 Grinding

4.6 Machining our gearwheel

Having described some machining processes, let's now consider whether they can be applied to the problem of making gearwheels for a food mixer. These wheels are quite complicated shapes. Could our gearwheel from the gearbox of the food mixer be made by machining? Of course, the answer must be yes because as discussed the outstanding virtue of machining is its versatility – almost any shape can be made by machining.

However, the complex shape means that a lot of waste material would have to be machined away if we cut it from a solid block of metal. Manufacturing a limited number of gearwheels by machining using these techniques is a labour-intensive process and would not lend itself to mass production. But for prototype manufacture, where only a few gears may be required, then this may be the most sensible option. In fact, a process called hobbing can be used for mass production of gearwheels as shown in Figure 46.

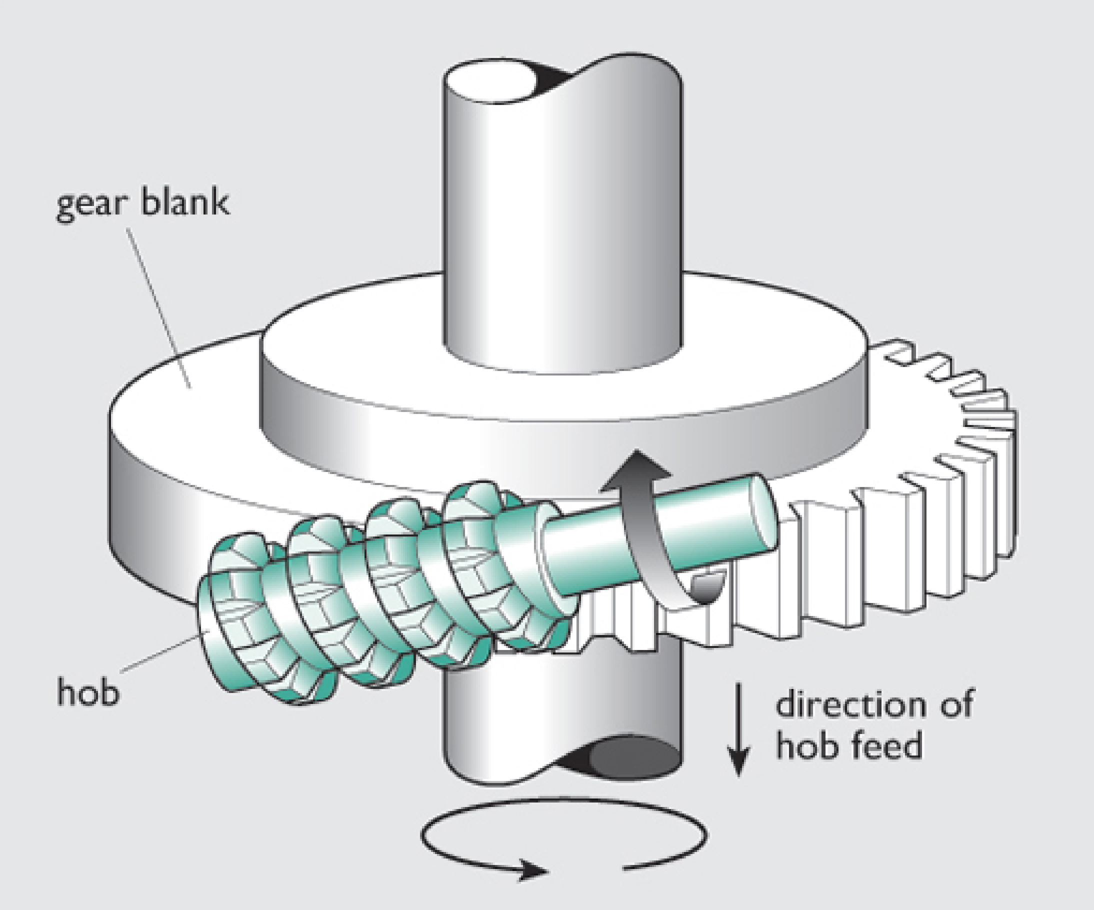


Figure 46 Hobbing a gear

So machining can also be added to our list of candidate processes to manufacture our gearwheel. We also may need to use a machining process to finish gearwheels made by another process.

SAQ 9

If you were considering manufacturing ballpoint pens, do you think the machining option could be used?

Would machining be feasible for a mass-produced pen body?

Answer

Because of its versatility, machining could certainly be used to manufacture pens, but not as a mass-produced item. It would more likely be used as a limited production process at a high cost.

5 Joining

5.1 Introduction

In addition to manufacturing an individual component using a single casting, forming or cutting process, we could assemble it from a number of simpler shapes joined together. There are other reasons for employing joining in a manufacturing operation. A product can be too big to make in one piece. The need to transport the product from the place of manufacture to its destination may limit the processes that can be used – it is often simpler to transport the product in parts, and assemble these parts at the relevant location. The building of a house or super-tanker are obvious examples. Joining can also be useful if a product has a complex shape, or if there is a need to combine different materials together. All these factors make it advantageous to join together previously shaped components in order to fabricate a complete and useful product.

In general terms, there are three basic methods of joining material together:

- *Mechanical* joints using fasteners where the elastic and/or frictional properties of a material are exploited to hold two components together physically (rivets, nuts and bolts, screws and so on).
- *Gluing*, where a layer of another material is introduced between two surfaces and later solidifies to form a solid joint.
- *Welding*, where the aim is to create a joint between two surfaces which is similar to the bulk material.

Although you can join things with simple glues or even Sellotape, here we will be concerned with methods of joining solid components in such a way that the joint will remain intact throughout its service life. The designer's aim is to select a joining process and a joint geometry such that the joint itself is not the weak link in the chain. Of course, joining techniques are also available that allow the joints to be taken apart at some time in their lives.

5.2 Mechanical joining

In mechanical joints, various methods are used which clamp or fasten the parts of the assembly together (e.g. nails, screws, bolts, rivets and circlips). Mechanical joints find innumerable applications from cheap plastic toys to aircraft bodies. They are versatile, easy to use, allow dismantling of the product and permit different materials to be joined with ease. Fountain pens and gearboxes are typical examples; many pens screw together in two sections so that the ink cartridge can be replaced, and gearboxes can be dismantled for maintenance. Mechanical joining also allows movement of components relative to one another, for example, by the use of hinges and bearings.

Mechanical joints do have disadvantages – the fasteners join at discrete points and do not, by themselves, seal the joint against the passage of liquids and gases. Gaskets (such as rubber ones that seal washing machine doors), and the silicone bead around the bath or shower tray, are typical methods of sealing joints, but almost all the other joining methods that are examined in this section form a continuous connection between surfaces and therefore seal the joint without the need for these additional materials. The hole that the fastener goes through in a mechanical joint is a potential weak spot and failure often occurs at these sections (remember that stress = force ÷ area, so by reducing the load-bearing area the stress is increased). If account is not made for this during the design stage then problems may arise during service. In a Boeing 747 (Figure 47) there are 6 million parts, of which 3 million are fasteners of some kind and about half of these fasteners are rivets – that is a lot of joining!

Figure 47 A typical wide-bodied aircraft can contain several million fasteners

5.3 Adhesive joints

The essential feature of adhesive joining is that two parts are joined by placing a liquid between them, which then solidifies. The strength of the joint depends both on the strength of bond between the parts and the adhesive layer, and the strength of the adhesive layer itself. In **Brazing and soldering**. the layer is put in as a hot liquid which solidifies on cooling to room temperature as shown in Figure 48.

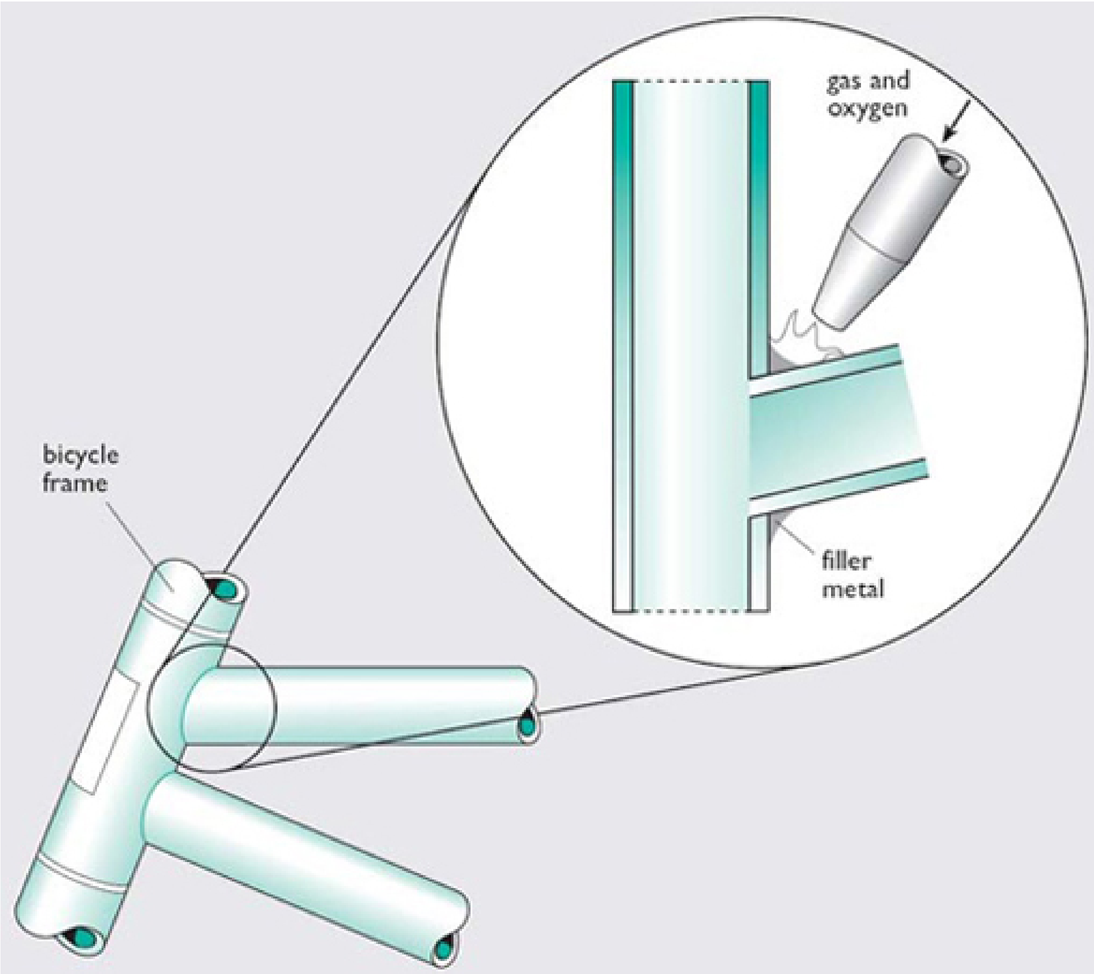


Figure 48 Brazing and soldering

5.4 Brazing and soldering

Brazing is defined as the joining of metals using a filler rod which melts at temperatures above 450°C but below the melting temperature of the metals being joined. Typical features of the brazing process are:

- the brazing alloy can be significantly different from the base material because the base material does not melt;
- the strength of the brazing alloy is substantially lower than the base metal;
- bonding requires capillary action, where the brazing liquid is drawn into the joint.

And because of these differences, the brazing process has several distinct advantages over welding:

- virtually all metals can be joined by some type of brazing metal;
- the process is ideally suited for dissimilar metals;
- the lower temperature than that needed for welding (welding is discussed shortly) means the process is quicker and more economical;
- the low working temperature reduces problems with distortion that can occur during welding, so thinner and more complex assemblies can be joined successfully;

- brazing is highly adaptable to automation and performs well in mass production.

Soldering is defined as a brazing-type operation where the filler metal has a melting temperature below 450°C. The bond strength is relatively low compared to brazing. The 'traditional' solder alloy is based on a tin/lead mixture, but lead-free alloys are becoming more commonplace.

5.5 Glues

The word 'adhesive' is usually taken to mean a type of glue. Adhesives now come in a vast array of different types; some stick in seconds (cyanoacrylate – Superglue), some take a day or so to cure (thermosetting epoxies), others stay permanently in a soft flexible state, like silicone adhesives. *Thermosetting glues*, like thermosetting plastics, are made by mixing together two ingredients, a 'resin' and a 'hardener', usually in liquid form, which react chemically to form a solid.

The major advantages of adhesive bonding are:

- almost all materials or combinations of materials can be joined;
- for most adhesives the curing temperatures are low, seldom exceeding 180°C;
- a substantial number cure at room temperature and provide adequate strength for many applications;
- heat-sensitive materials can be joined without damage;
- no holes have to be made as with rivets or bolts;
- large contact areas means high joint strength;
- the adhesive will fill surface imperfections.

The major disadvantages of adhesive bonding are:

- most adhesives are not stable above 180°C;
- surface preparation and curing procedures are critical if good and consistent results are to be obtained;
- life expectancy of the joint is hard to predict;
- depending on the curing mechanism, assembly time may be longer than alternative techniques;
- some adhesives contain toxic chemicals and solvents.

For successful soldering or adhesion, the 'glue' material must 'wet' the surfaces of the two objects to be joined. You can see the contrast between wetting and non-wetting when washing up greasy breakfast plates. When the plates are covered with oil and fat, water just runs off without sticking. This contrasts with what happens when the fat is removed with hot water and detergent: the plate then retains a thin covering of water. We say that water is 'wetting' the clean glazed surface.

Successful joining by solders or adhesives usually requires that the surfaces to be joined are completely clean. This can be achieved by using either mechanical or chemical techniques. The mechanical method uses abrasion to clean the surface, while the chemical methods for preparing metals typically use acidic solutions which etch the surface, as well as degreasing it with solvents. After cleaning the surface it is vital that recontamination does not occur from oxidation and airborne pollution. In particular, when heat is applied during brazing and soldering, oxidation can rapidly take place; in this case a flux can be applied which prevents oxygen from reaching the prepared surface. Abrading also has the advantage that the surface is roughened, thereby increasing the surface area which enhances the contact area of the joint.

5.6 Welding

An ideal welded joint between two pieces of metal or plastic could be made by softening the materials sufficiently so that the surfaces fuse together. Bonding forces hold the atoms, ions or molecules together in a solid. From this, it could be argued that if we simply bring together two samples of the same material, they should spontaneously bond together as soon as they approach to within some critical bonding range of one another (of the same order as the spacing of the bonded units in the material).

In practice, this 'bonding on contact' is frustrated by two complications. Firstly, it is extremely difficult in this macroscopic world to shape two surfaces so that they really fit together. Usually, surfaces have a roughness, with an average height far in excess of the range of bonding, and when two such surfaces are brought together they will 'touch' only at the 'high' spots (rather like trying to get two pieces of sandpaper to mesh together precisely). Secondly, surfaces are often chemically contaminated. Most metals are very reactive and in air they become coated with an oxide layer or with adsorbed gas. This layer prevents intimate contact from being made between two metal surfaces.

Clearly then, to achieve bonding on contact:

- the contaminated surface layers must be removed;
- recontamination must be avoided;
- the two surfaces must be made to fit one another exactly.

5.7 Solid-state welding

In highly deformable materials, such as metals and thermoplastics, the above aims can be achieved by solid-state welding, that is, forcing the two surfaces together so that plastic deformation makes their shapes conform to one another. At the same time the surface layers are broken up, allowing the intimate contact needed to fuse the materials without necessarily melting them. This was the principle of the first way known to weld metals – by hammering the pieces together whilst hot. It is not always essential for the parts to be hot; ductile metals such as gold can be pressure welded at ambient temperatures. Processes that join without melting the material are called solid-state welding.

Solid-state welding can be carried out in various ways. For example, two metal sheets laid over each other can be welded together by rolling – 'roll bonding'. Bimetallic strips for thermostats are made this way. Deformation of the surfaces can also be done in more exotic ways such as rubbing the two surfaces against one another (friction welding) or by using explosives to fold one sheet of metal against another (explosive welding).

In solid-state welding, there is a small melted zone, but the melted matter is usually 'squeezed out' when the parts are pushed together, so the join is a solid-state one. Commonly polyethylene gas pipes are welded using heat and pressure. In this case a heated plate is used to generate the heat on the two surfaces. Once hot, the plate is removed and the pipes are forced together under pressure, thereby forming a welded joint. The *heat sealing* of thermoplastics works on the same principle. Two layers of plastic sheet that are to be joined are overlapped and compressed between heated tools. This forces the materials together and the joint is made because of the intimate contact between the surfaces.

5.8 Fusion welding

In fusion welding, the parts to be joined are brought together, melted and fused to each other. In some processes the interface is filled with a molten substance, supplied by a filler rod that is similar in composition to the materials being joined.

During fusion welding the areas that are being joined comprise an intimate mixture of parent material, and filler rod (if one is used), within the welded zone. In all methods of fusion welding, heat must be supplied to the joint in order to melt the material. Inevitably, temperature profiles are created and the resulting differential expansions and contractions can cause distortion, and in extreme cases, the formation of cracks, in the assembly. As welds are, in fact, small castings, welds contain both the microstructure and porosity endemic in cast material.

Soldering and brazing can minimise some of these problems, as the parent material is not melted, so temperature profiles are not as great. But in brazing and soldering there is a discrete join between the materials as opposed to an intimate mixture of material in welding; welding is by far the strongest of the processes.

5.9 Joining (assembling) our gearwheel

Whilst we cannot make our food mixer gearwheel just using joining processes, we could assemble it out of several pieces which must be joined together. In practice, any of the joining processes (soldering, adhesion and welding) would allow the wheel to be built up from bits. Wooden gearwheels and waterwheels used in mills many years ago, known as cog wheels, were made by assembling individual parts which could easily be repaired if any wore out after prolonged use. However, these were on a different scale from that of a gearwheel from a food mixer. So although building a gear would be possible, it is not really a practical proposition. Imagine trying to build a gearwheel from parts; each tooth would need to be manufactured individually and then screwed, glued or welded together to the central ring. A great number of hours would be spent manufacturing each one.

Although the gearwheel itself is not suitable for being made through an assembly process, it is itself assembled into the food mixer, which has many discrete parts, made from a range of processes. There is always a stage at which a single product is likely to be assembled in some form into a larger product for a particular use.

SAQ 10

List three advantages and three disadvantages of using joining processes in manufacturing.

Answer

Some advantages are:

- joining enables large objects to be built up from smaller, more manageable components.

- joining allows dissimilar materials to be joined.
- practically speaking, most functional objects require joining because they cannot be made in one piece.
- heat-sensitive materials can be joined at room temperature.

Some disadvantages are:

- joints may be a weak point in a structure, and even welded joints will not have the strength of the individual materials that are joined.
- surface preparation can affect the joint properties if adhesives are used, the design life of a joint may be hard to predict.

You may have suggested other, equally valid, factors.

6 Making the gearwheel

6.1 Introduction

Our short review of manufacturing processes is now complete. There are many processes which have been omitted, but in the main they are variations on or adaptations to the major processes that have been examined. As you have discovered, the gearwheel that has been used as an example through this part could have been made by any of the processes, albeit with considerable difficulty in some cases! So let's see how the gearwheel is actually made.

For some years, the gear in Figure 10 has been made from sintered iron powder, in which form it gives trouble-free service (Figure 49). This design replaced an earlier one in which a wheel of identical shape was made from injection-moulded nylon (Figure 50). There were some cases of fracture in the plastic wheels due to overloading in service (some owners must have liked particularly stiff dough for their pizzas), so it was decided to use a stronger material. This illustrates that redesign after service experience can be crucial to the success of a product. In this instance, actual service conditions revealed a basic flaw in the original design: the original estimate of the strength required by the gear proved to be somewhat inadequate. Stress analysis may be an exact science, but the estimation of forces from use and abuse is not and must be based on experience.

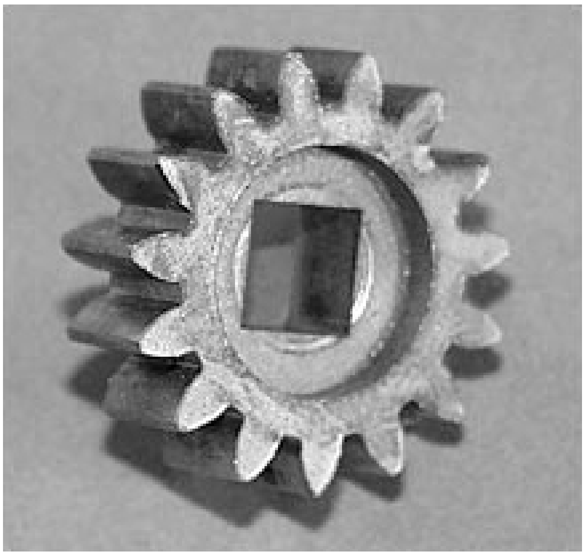


Figure 49 Sintered iron gearwheel

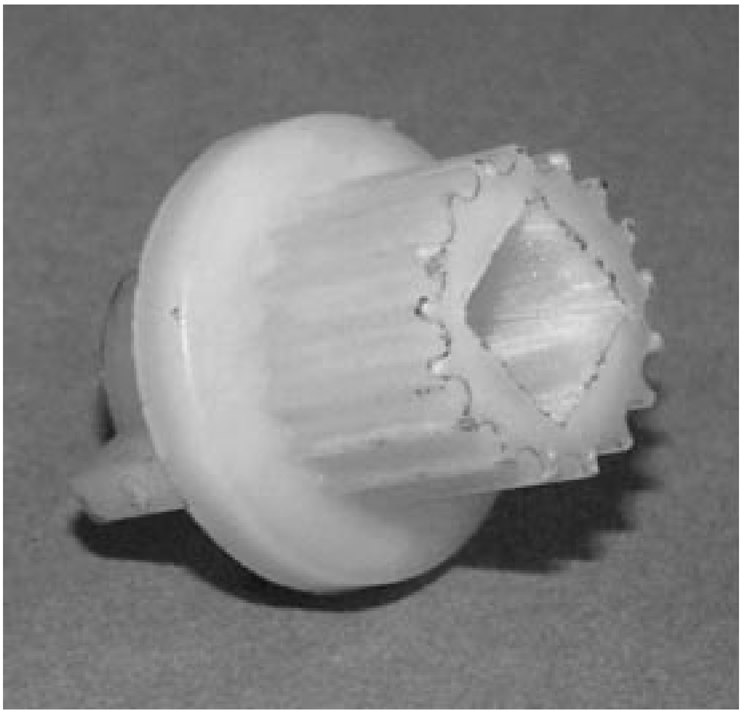


Figure 50 Injection moulded gearwheel

6.2 Production costs

By comparing the unit costs of making 10^5 gears of this type by all the feasible processes considered earlier, it should be possible to identify why this particular process was adopted.

Table 1 lists a number of processes, and the cost per unit for two cases: if 100,000 are made; and the cost to make just one, perhaps for a prototype.

Table 1

Process	Material	Unit cost for 100,000 gears	Cost to make one prototype
Pressure-die casting	Zinc	0.19	9600
Sintering	Iron	0.24	16,000
Injection moulding	Nylon	0.29	9600
Extrusion	Aluminium	0.35	1240
Gravity-die casting	Aluminium	0.37	1200
Machining	Mild steel	3.6	100

Exercise 4

What factors influence the choice of production method for a prototype or for a full production run?

The prototype will not be for sale; it is made to ensure that the design will be a viable and operational product. Because only a few are made, the materials and processes used may not be exactly the same as for the final version. Certainly there will be no investment in a production line for making a few prototypes, as there may be further amendments to the design after the prototype stage.

A production run will require large-scale investment in machinery, and will commit the company to producing and selling the product.

The costs are normalised arbitrarily to 100 'currency units' for making one prototype by machining, and are therefore relative costs rather than absolute.

The cheapest process is pressure-die casting in zinc alloy. However, since the strength of a nylon gear proved to be inadequate and the strength of zinc alloy is comparable (see Figure 51), this choice was unsuitable. For iron, pressure-die casting cannot be used (what would you make the die from?!), and the second process in the list is the next cheapest – sintering. This is the choice of the manufacturer.

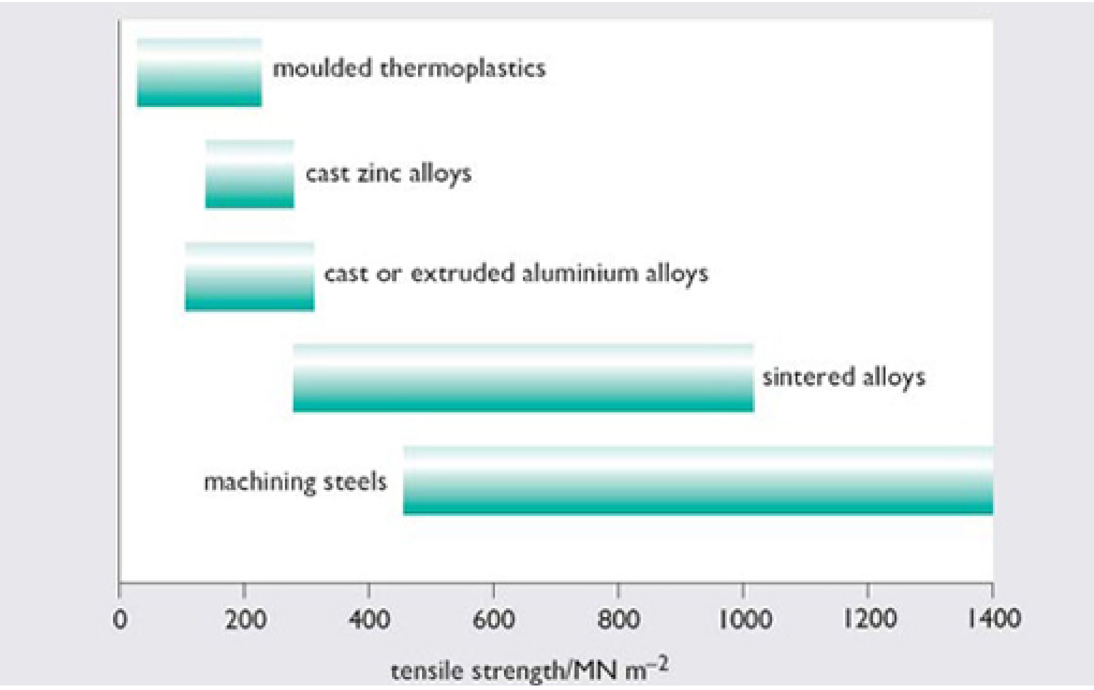


Figure 51 Approximate strength ranges for a selection of candidate gear materials

What would the manufacturer's choice have been for the production of a prototype? The unit costs for producing one gear are also set out in Table 1 and they lie in a quite different order from those for mass production. This arises because the tool costs tend to dominate when they are not written off over a large number of products. The cheapest process is machining because its special tooling requirements are the most modest. This process requires only relatively simple cutting tools and standard workshop machine tools; it is also probably the quickest process to use for making a prototype. On the grounds of both cost and time, machining is the preferred method.

6.3 Looking ahead

All these choices represent a best attempt to provide adequate performance by the gears at *minimum cost*. 'Adequate' means providing trouble-free service for a given design life. Notice that when the material is changed (for example, from nylon to iron), then so too does the preferred manufacturing process. Clearly it is the *properties* of a material (such as its strength) which decide whether the product will have adequate performance, and it is also the properties (such as the way the material melts) which decide how the product can be made.

This interdependence between properties, the product, the process and the price is complex. However, you should now be aware that there is a vast array of processes available to the manufacturer for the production of a particular component, and you should know a bit more about materials' properties, so that you can begin to understand the reasoning behind adopting a particular processing route.

7 Surface engineering

7.1 Introduction

So far we have considered how we might manufacture an artefact from a single material, or at most by joining together two components made from different materials. Quite often, however, the key properties we require from a product apply mostly to its surface. We may require it to be hard, or corrosion resistant, or we may want a colourful aesthetic effect. Under these circumstances, it can be more practical and cost effective to just change the properties of the surface rather than the whole artefact. This approach is known as surface engineering.

By engineering the surface layers of a product, desirable properties can be imparted. Whether this surface layer provides a protective coating, modifies or enhances the properties of the product, or is simply cosmetic to improve the aesthetic appearance, is a matter of design. Manufacturers of products now have a selection of processes with which they can improve their product. I will describe a few of these techniques in this section, together with examples of their use.

Life is full of compromises, and engineering is no different. Often, one set of properties is desired of the materials in making a component, but those properties are not suitable for either the manufacture or the overall performance of the final product.

Think about the car: one of the main factors in limiting the life of a car is the degradation – by corrosion – of the bodywork. In principle, we could make cars out of stainless steel, but the cost of the car would soar. Aluminium is better at resisting corrosion than steel, so in this case it is clear that we could make the body out of a choice of materials. This choice might include aluminium, plastics or steel.

In fact, the majority of cars in the UK are made from mild steel (steel which contains a small addition of carbon, typically up to 0.2 per cent carbon). This is an ideal choice for mass production in that it can be easily formed to the correct shape, can be joined by simple welding processes, and it is relatively cheap and light. However, if it were left as a bare mild steel body, it would soon be rusted completely through. Therefore cars are often galvanised (the surface is coated with a thin layer of zinc) and always painted. Such is the confidence in this surface process that cars are now available with up to 12 year anti-corrosion warranties. This is an example where the paint itself would not be a choice as a structural material. Therefore the steel is being 'surface engineered' to give the desired properties.

In surface engineering, improvements are made to the performance of a component by applying a coating or by actually modifying the surface of the material itself. Here I am going to discuss coating methods which change the performance of a product without necessarily affecting the properties of the bulk material. One of the important points to realise about surface engineering is that the layers of material that are added are often very thin. For a car, the total paint coat is usually <200 μm thick – i.e. about twice the thickness of a hair on your head – and the change in the component behaviour that the paint confers is out of all proportion to its thickness.

The benefits of surface engineering are illustrated by two case studies.

7.2 Case study 1: The kitchen knife

A kitchen knife is an everyday item that can be treated by surface engineering to greatly improve its performance. Great demands are made on kitchen knives: they are expected to retain their sharpness without regular sharpening, and they must withstand the corrosive environments that they encounter. Corrosion can arise from the natural acids contained within some foods, or the hot and humid conditions encountered in a dishwasher – including the corrosive nature of dishwashing powders.

Domestic knives are almost all now made from **Stainless steel** strip. Depending on the knife, the strip can vary in thickness from 0.5 to 3.0 mm, with better quality knives generally being cut from thicker strip. Initially, the strip is supplied as a coil and the basic knife shape is 'blanked out'. The profile and cutting edge of the blade are then ground onto the edge of the strip by passing the knife through a series of grinding wheels. This process is outlined in Figure 52. Finally the knife is polished to give it an aesthetically pleasing appearance and to reduce the possibility of food sticking to the surface.

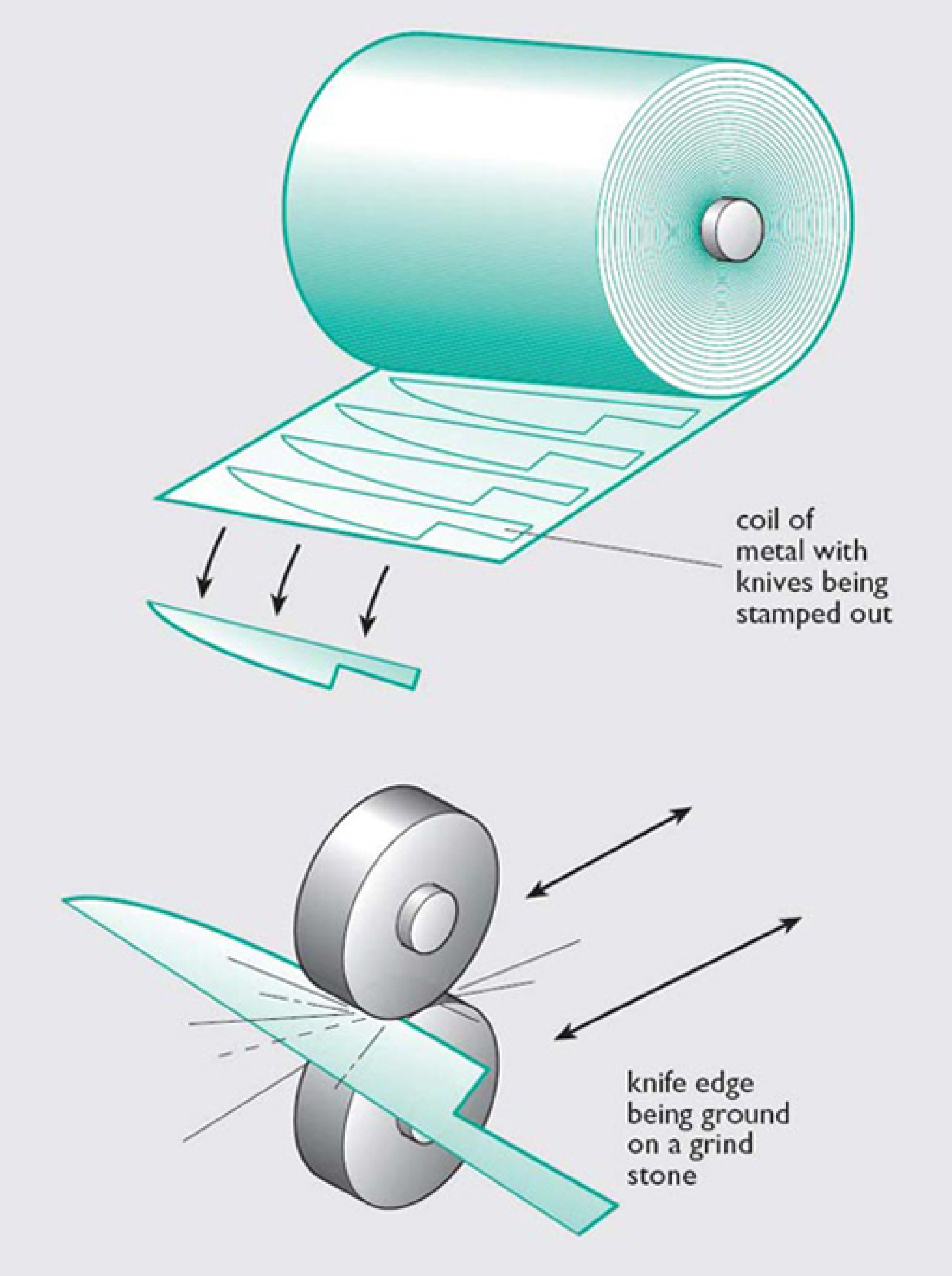


Figure 52 Knife production

Once the knife has been produced, a handle is fitted. In some knives, the handle attaches to a short 'tang' (the projecting end of the blade which allows the blade to be held firmly in the handle), and in other knives, the tang runs completely through the handle. A full tang offers a more rigid handle and therefore tends to be used on higher quality knives. The tangs are shown in Figure 53. The handle of the blade can be made from numerous different materials, such as wood, polymer or even stainless steel!

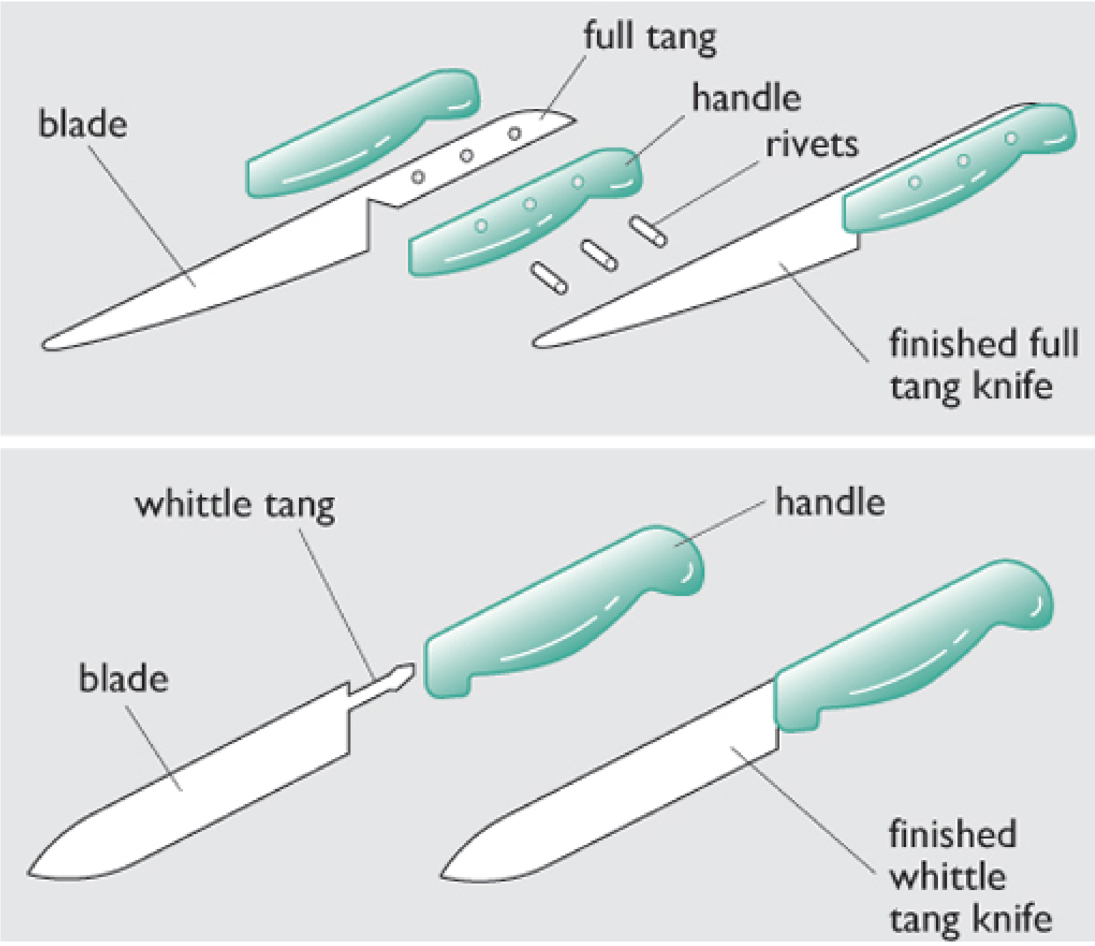


Figure 53 Knife tangs

The most important property for a knife is its sharpness: it should be sharp enough to cut vegetables, etc., and it should stay sharp, and not become blunt after only a few uses.

If we want to improve the cutting performance of a knife, it might be better to improve the way in which the sharpness is retained rather than make the blade sharper. Indeed, sharper blades tend to blunt faster, because of the higher stress at the blade edge (a sharper blade carries the cutting load over a smaller area).

So is better sharpness retention possible without resorting to surface engineering? Let's examine a few possible strategies.

7.2.1 Increase the hardness of the steel

One way of preventing blunting is to make the steel harder. Steel can be made harder by changing the alloying elements in the steel and then heat treating the material after the knife has been manufactured. The problem with this route is that the alloying elements which make the knife harder detract from the corrosion resistance of the knife. Therefore a balance must be found between simply making the knife harder and making it less corrosion-resistant. Generally, the hardness of a range of kitchen knives from cheap to expensive is controlled to be in the range of 500–600 HV. However this hardness is still insufficient to prevent**Wear**and the knife will eventually need resharpening.

7.2.2 Make the knife out of a harder material

If we want to use a harder material, the obvious first step is to look at ceramics, which are much harder than steel (see the table of hardness values in Appendix 1). The hardness of alumina (a typical engineering ceramic) is approximately 2500 HV compared to a hardened steel 600 HV; but can ceramics be used to make a kitchen knife?

The major drawback to this is that most ceramics are too brittle for kitchen applications: drop one on a tiled floor and you have the same result as dropping the best china (also a ceramic).

Nonetheless, by careful manufacture it is possible to make knives from some ceramic materials. Ceramic sushi knives are now available (Figure 54) which are made from a material based on zirconia, which has a hardness of ~1300 HV, and can be engineered to have toughness high enough to withstand the impact loading imposed by dropping. The combination of high hardness and improved toughness leads to a knife which has superior sharpness and longevity. However, for the mass market, this knife has the drawback that it has to be carefully treated and it is not suitable for cutting all types of food, such as meat, which is tougher than fish. Not a great attribute for a kitchen knife; novelty value maybe – at a cost.

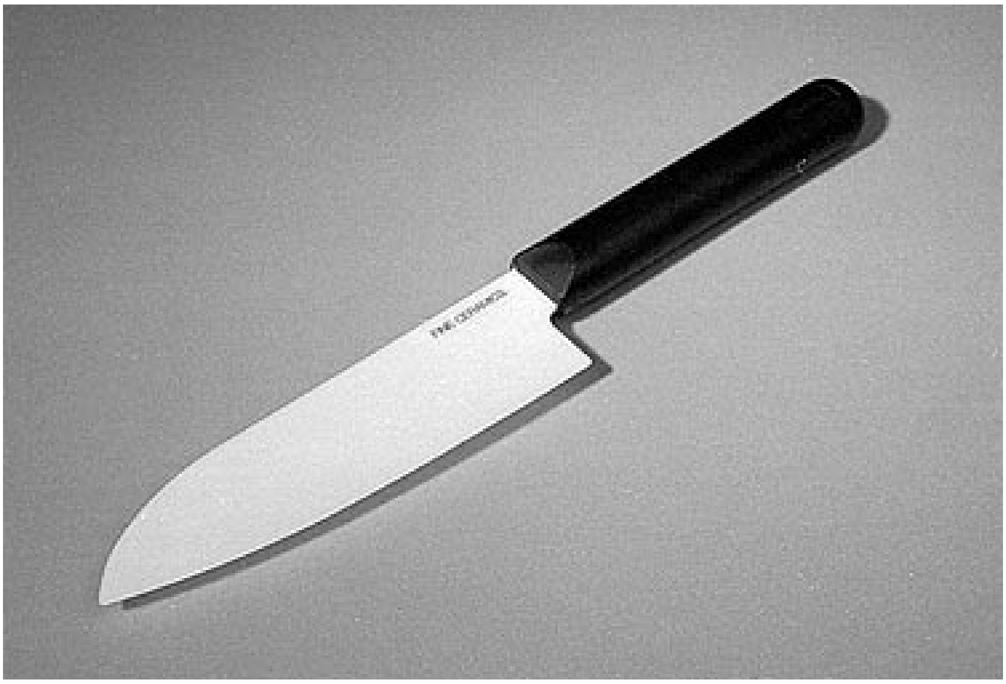


Figure 54 A ceramic kitchen knife

7.2.3 Engineer the cutting edge to retain the sharpness

The next stage is therefore to see if surface engineering can bring about an improvement in the edge retention. The chemical composition of the surface layer of a material can be altered by implanting additional alloying elements into the surface. Using a method like this, an increase in hardness can be achieved. This increase will only occur in the surface layer.

There are three thermochemical (so-called because they use a combination of thermal and chemical effects) processes which can be used to treat steel in order to improve hardness: they are carburizing, nitriding, and carbonitriding.

Thermochemical treatments in general involve soaking the components in a bath of chemicals, or exposing them to a suitable atmosphere which contains the desired elements. These elements then diffuse into the surface of the part that is being treated. Simply, diffusion is a process by which atoms move from a high concentration of themselves to a lower concentration. Thus, if a steel component has a low concentration of carbon, and the bath that it is placed into has a high concentration of carbon, then there is a tendency for the carbon atoms to diffuse into the steel.

Processes where carbon diffuses into a material are known as *carburizing* treatments. Other treatments are *nitriding*, which enriches the surface layer with nitrogen, and *carbonitriding*, where both carbon and nitrogen are diffused into the surface. Components that have been treated in this way are then heat-treated to optimize the mechanical properties of this surface layer.

In the case of a knife, the surface layer needs to be hard while the body of the knife still needs to retain some measure of toughness. A fully hardened knife blade would be too brittle for domestic use. The hardness of a layer treated thermochemically and then heat-treated can be between 700 and 1200 HV.

A more recent surface engineering technology to improve the cutting performance of kitchen knives is to coat the steel knife with titanium nitride (TiN), a hard and wear-resistant ceramic coating. In this way, the benefits of ceramics are combined with those of steel. The coated knife retains its performance approximately 10 times longer than an ordinary steel knife. TiN coatings for knives are typically produced by **Physical vapour deposition**.

A further, even more recent, development is to use an alternative coating method known as **Plasma spraying**. Plasma spraying allows coatings of tungsten carbide (chemical formula WC) to be deposited which can give up to an 11,000 times improvement in edge retention over an uncoated plain edge knife.

To coat kitchen knives using plasma spraying, the knives are positioned so that they can all be sprayed in one process and so that the depth of the coating along the knife blade is carefully controlled. There is little point in coating the whole knife, as this would be uneconomic. Further, only one side of the knife blade is coated so that any wear causes the sharp edge to continuously regenerate itself, rather than having layers of coating being chipped away at the cutting edge. One of the advantages of the plasma-spraying method is that much thicker coatings can be used. The coating applied here is approximately 30 μm in thickness compared to the PVD coating which is 3–4 μm in thickness. For this application, the plasma-sprayed coating is more effective.

7.3 Stainless steel

Steel is an alloy of iron and carbon. But it can also have other elements added to it to enhance its properties. Stainless steel has a minimum of 12 per cent chromium added to improve its corrosion resistance. The corrosion resistance of stainless steel arises from the formation of a thin protective film of chromium oxide on its surface. This film is highly resistant to chemical attack and if scratched (in air), the oxide layer rapidly reforms. The drawbacks to stainless steels are that they are readily attacked by chloride ions (in salt for example), and that the oxide layer does not form if oxygen is not present (not a problem for most domestic applications!).

There is a number of different stainless steels, and they are classified by the alloying elements that are present and the heat treatment that the steel has received. Stainless steel is widely used for cutlery and different cutlery has different compositions. One example contains the following alloying elements: 14 wt% chromium, 0.04 wt% carbon and 0.45 wt% manganese (these figures tell us the percentage, by weight, of the alloying additions in stainless steel, the balance of course being iron). This alloy of steel is widely used for producing forks and spoons where a high hardness is not required, as there is no need for a cutting edge, and the steel produced is ductile, formable and easily shaped from thin sheets.

A slightly more expensive type of stainless steel is known as 18/8 stainless steel. This has the composition 18 wt% chromium, 8.5 wt% nickel, 0.8 wt% manganese and 0.05 wt% carbon, (the 18/8 'label' comes from the chromium/nickel composition). This type of steel is more expensive because nickel is a costly alloying addition. This steel is non-magnetic (if you go through your cutlery with a magnet, you should be able to differentiate between the two types of steel by seeing which of your knives and forks are magnetic!). 18/8 steel is ductile and can be formed into shape by cold-forming, which also has the benefit of increasing the strength through work hardening.

The type of stainless steel used for kitchen knives would have a typical composition of 13 wt% chromium, 0.3 wt% carbon and 0.4 wt% manganese. The higher carbon content means that this steel can be hardened and then tempered to give a Vickers hardness in the range 500–700 HV. A small amount of the element molybdenum is added to this steel, as well as to 18/8 steel, which improves the resistance to attack by dishwashing powders and salt water. The Thames Barrier is made from an 18/8 stainless steel (as are many ocean-going yacht fittings) with 3 per cent molybdenum added.

7.4 Wear

Wear can be defined as the unintentional, progressive loss of material from a surface. All surfaces are rough at the microscopic scale. Figure 55 shows the trace taken of a surface using a stylus profilometer (this is like dragging a record player stylus across the surface of a material and measuring the vertical deflection). The surface has considerable variation as can be seen from the peaks and troughs. These peaks are termed *asperities* and these are important in wear as hard, sharp asperities may plough into a softer material. In addition, when two surfaces are touching, it is the tips of the asperities that contact rather than the overall surface, so the true contact area between the surfaces is a lot smaller than you may think. This means that the friction can be controlled by how the asperities bear the load and deform. It also influences the way in which the materials wear.

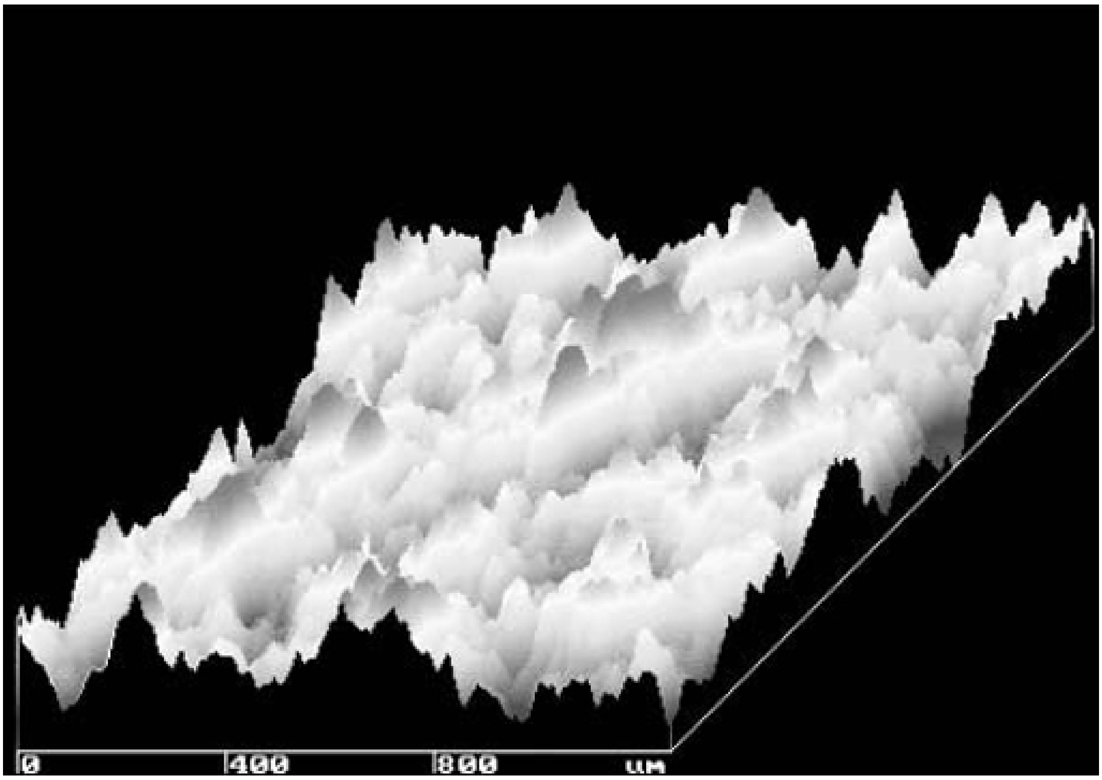


Figure 55 Profilometer trace of a 'super-smooth' silicon wafer (the magnification of this image is larger in the vertical scale than the horizontal). The height distance between the peaks and the troughs is about 3 nanometres

7.5 Physical vapour deposition

Physical vapour deposition (PVD) processes involve depositing a source material (which can either be from a solid, liquid or gas) onto the surface of the component. There may be a chemical reaction between the substrate and the coating material. One of the attractions of PVD methods is that the substrate can be at relatively low temperatures (in the range 50–500°C). Figure 56 shows a schematic diagram of the principles behind one common PVD method.

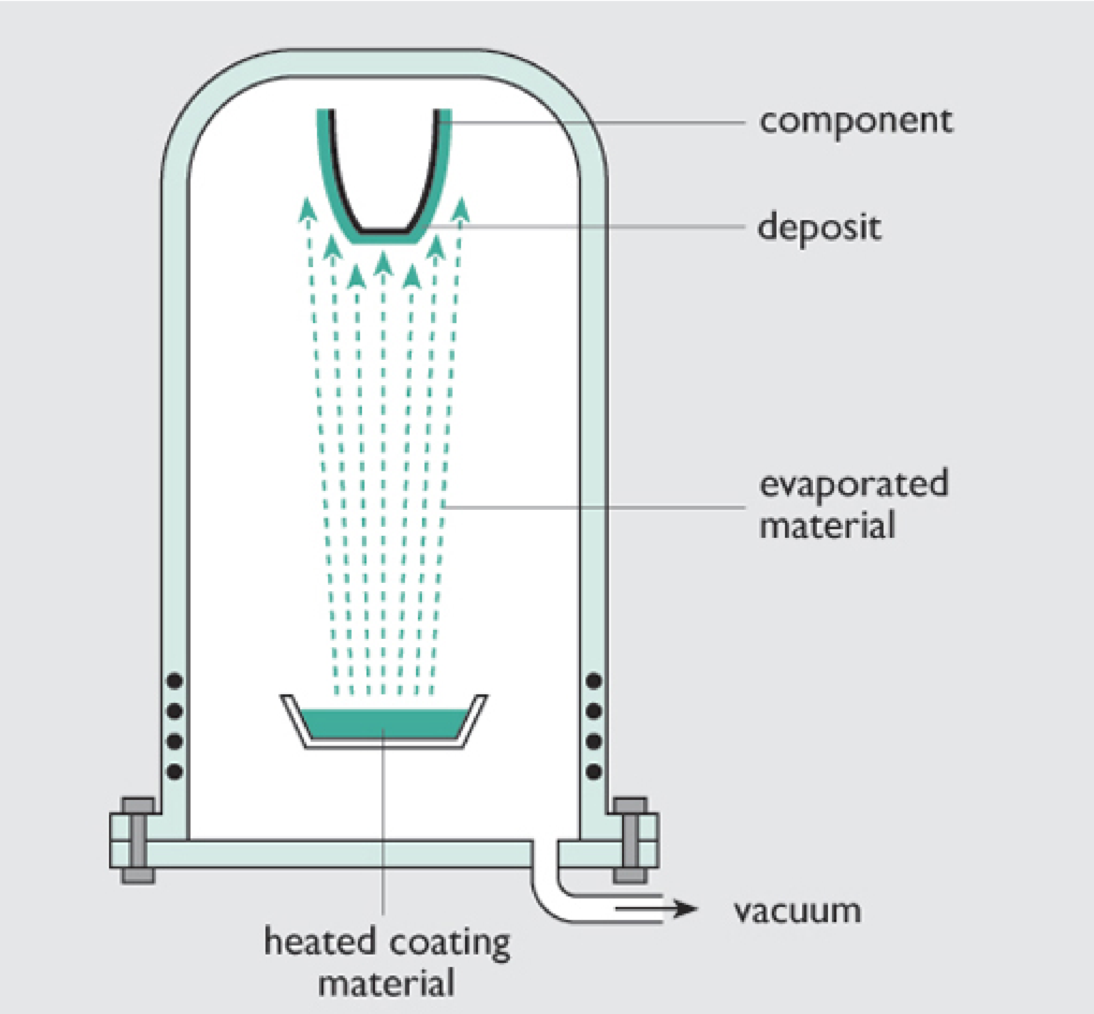


Figure 56 The vacuum evaporation PVD process

The component that is to be coated is placed in a vacuum chamber. The coating material is evaporated by intense heat from, for example, a tungsten filament. An alternative method is to evaporate the coating material by a complex ion bombardment technique. The coating is then formed by atoms of the coating material being deposited onto the surface of the component being treated.

The 'ion plating' method is used commercially to produce films of titanium nitride (TiN) such as the one used for coating kitchen knives.

7.6 Plasma spraying

A number of processes have been developed where particles of coating material are heated to a molten state and projected at a substrate which is relatively cold (<200°C). The density of the coating and the adhesion of the coating to the substrate are controlled by the speed at which the particles impact on the substrate.

A plasma – a superheated gas – is formed by using an inert (unreactive) gas such as argon with a small amount of hydrogen or helium and then applying a high energy electric arc at typically 40 kV. The material for the coating is fed into the gun, as a fine powder, down the powder feed. The powder melts in the plasma and the gas expands rapidly and accelerates the molten droplets to speeds of 250–500 m s^{-1}. The process conditions must be carefully controlled so that the coating adheres well to the substrate. This ensures that any friction and wear causes the coating to wear away rather than peel away from the surface. Ideally, the coatings that are produced have low porosity and good mechanical strength.

7.7 Case Study 2: Optical coatings

Should you need spectacles, you will doubtless be aware that opticians can now offer a bewildering choice of different materials and an array of surface treatments to enhance the spectacle lenses, from antiglare coatings to scratch resistance. How do you decide whether to pay for the extra protective coating that is offered and should you choose glass or plastic lenses? What are the materials properties that are important and why are coatings required? The terminology contained in **Optical terms** will help you work through this section.

7.8 Optical terms

7.8.1 Refractive index

Refractive index (given the symbol *n*) is an important optical property, as it is a measure of how much a particular material can change the direction of a ray of light (i.e. refract it) as it passes through that material. A high refractive index material will change the direction much more than a low one, so the material for a spectacle lens, which has to bend the light rays to the correct angle for the eye, can be made thinner.

Refractive Index, *n*, can be expressed as the change in the angle of light passing into a material, hence

$$n = \frac{\sin i}{\sin r}$$

where *i* is the angle that the light makes when it is incident ('shining') on the material and *r* is the angle that it is refracted through (Figure 57).

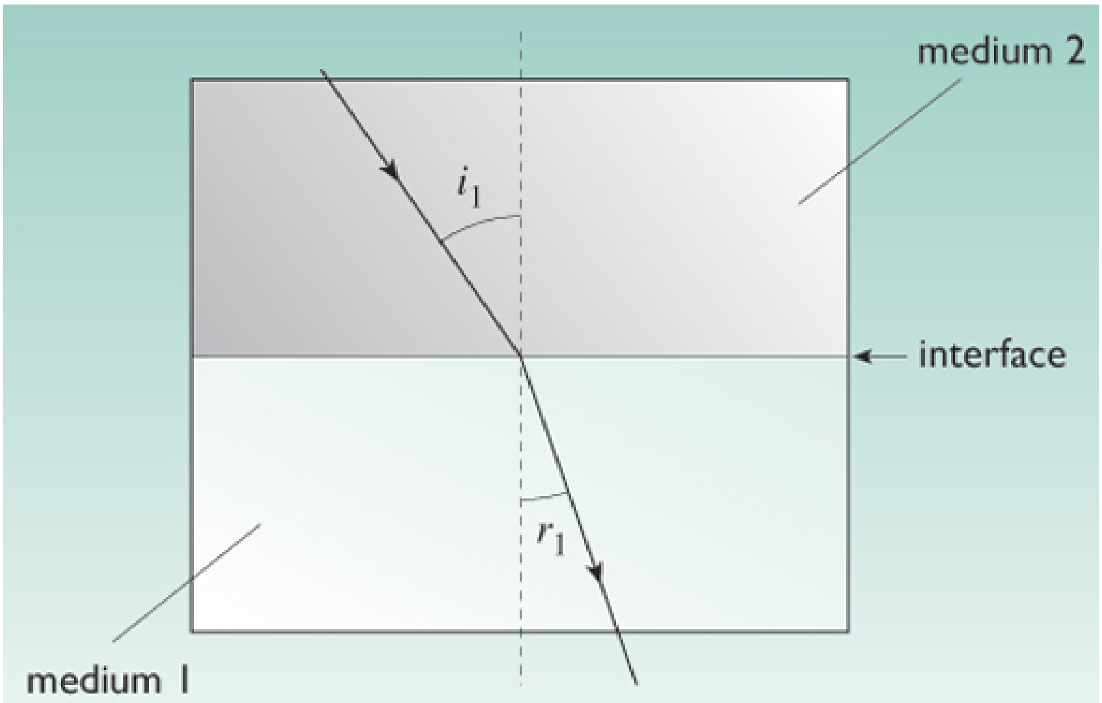


Figure 57 Change in direction of light passing from one material to another

7.8.2 Dispersive power

Dispersion is important in the selection of materials for lenses as it provides a measure of how different wavelengths of light are separated. White light comprises different colours of light from the electromagnetic spectrum, from red through to violet (and all the rainbow of colours in between). The different colours have different wavelengths, and ideally you do not want these to separate as they are transmitted through the lens, or objects will appear to have coloured haloes around them. The degree to which a material disperses light (refracts different wavelengths by different amounts) is known as the dispersive power, *D*. So for lenses, a low *D* is desirable.

7.8.3 Scattering

If a rough surface is placed in a path of light then the scattering can be significant. This occurs as the light rays bounce off in different directions at different points along the surface. This is the principle behind frosted glass for bathroom windows. Spectacle lenses are therefore highly polished to minimise the scattering of light. It is also important that the lenses maintain their polished surface. So, in order to maintain lenses that do not significantly scatter the light, a way has to be found of improving the abrasion resistance of lenses.

7.9 Materials selection

What properties does a spectacle wearer require from the lenses in the spectacles? Well, first and foremost, the lens must transmit light and not distort the image. Secondly, as spectacles need to be worn for prolonged periods, ideally the lens should be of low weight. The material must be stable over a range of temperatures – the geometry of the lens must not change with variations in temperature. Finally, the material should not become scratched with everyday use.

There are five common choices of materials for spectacle lenses. These are: glass; so-called 'high refractive index glass'; the polymer polymethylmethacrylate (abbreviated to PMMA); CR39 (a thermosetting polymer); and polycarbonate. Both PMMA and CR39 are available with a 'high' refractive index. 'High' simply means that the polymer or glass has a refractive index higher than normal glass. The typical properties of these five materials are listed in Table 2.

Table 2: Typical properties of lens materials

Material	Refractive Index	Dispersive power	Density/ kg m^{-3}	Toughness/ MN $m^{-3/2}$	Vickers hardness/ HV	Abrasion resistance
Glass	1.52	1.72×10^{-2}	2530	0.8	490	High
High index glass	1.60–1.80	$\sim 3 \times 10^{-2}$	3900	0.5	590	High
Poly (methylmethacrylate), PMMA	1.50	1.89×10^{-2}	1190	1.15	20	Medium
CR39	1.50	1.72×10^{-2}	1320	0.75	40	Medium
High index polymer	1.54–1.68	$\sim 3.1 \times 10^{-2}$	1350	~0.3	~100	Medium
Polycarbonate	1.59	3.33×10^{-2}	1200	1.8	14	Low

The high refractive index materials may produce lighter lenses as they can produce much thinner lenses for the same bending of light. However, as with most material properties there are several trade-offs. Glass provides better scratch resistance than the polymers; however, the lens produced has additional weight. And although glass can be made with a higher refractive index than the polymers, its toughness decreases as its refractive index increases, so making the final lens more brittle.

PMMA and CR39 are generally cast by pouring them into a mould of polished glass plates separated by rubber. PMMA lenses can also be produced by injection moulding, which is faster, but has the drawback that a lower molecular mass PMMA must be used to allow the polymer to flow into the mould and this reduces the final toughness of the lens. However, it is a cheap process and high production rates are achieved.

Glass lenses are also formed in metal moulds which are approximately the correct curvature and dimensions for the lenses. Both plastic and glass lenses are finished using grinding and polishing machines. These dramatically improve the precision and reproducibility of the finished lens, and hence improve the subsequent optical performance of spectacles.

7.10 Scratch-resistant coatings

All polymer lenses ideally require coating to provide at least a similar scratch resistance to glass. The thickness of a typical scratch-resistant coating is about 2 µm. PMMA lenses are generally coated with a thin layer of the polymer CR39, which has a greater hardness than the thermoplastic PMMA. Other abrasive-resistant coatings are based on either using harder polymers such as polysiloxane, or using a silicate-based glass on the polymer surface. One of the critical factors with using scratch-resistant coatings is in ensuring that there is good adhesion between the coating and the lens.

Scratch-resistant coatings can be applied using PVD, an alternative method called chemical vapour deposition (CVD), or by methods such as dipping or spin coating. If the coating is being deposited onto a polymer lens, then special care must be taken with PVD to avoid heating and distorting or melting the lens material. The advantage of the dip or spin coating is the speed with which it can be applied. However, in some cases, a PVD or CVD coating can be much more effective.

Of the coatings available, one coating, called diamond-like-carbon (DLC) is particularly effective. DLC offers many of the properties of diamond, thus it gives a wear-resistant chemical barrier and can be applied to metal, ceramic, glass, and plastic. For spectacles, DLC has two main advantages: it is optically transparent and it is extremely hard.

DLC film is deposited by starting with a carbon-containing gas such as acetylene to provide carbon atoms to deposit onto the substrate.

DLC films have advantages in that their mechanical properties can be carefully controlled by varying the amounts of hydrogen in the deposition process. The properties of the film depend on the nature of the chemical bonding in the coating, and whether it most resembles the bonding in graphite or is more like that found in diamond – two substances that are composed entirely of carbon. For spectacles it is obviously important that the film is transparent, and fortunately, diamond, the harder of these two options, is also the more transparent. The mechanical properties of DLC can therefore be tailored to the requirements of a particular product simply by changing the deposition conditions.

7.11 Anti-reflective coatings

In a normal lens, about 4 per cent of the light is reflected as it passes through each side of the lens. This means that approximately only 92 per cent of the light reaches the eye. Some of the reflected light can form a *ghost* image by reflecting off the reverse side of the lens back to the front and then reflecting off the front into the eyes, as shown in Figure 58. An additional problem can arise from *flare* which is caused by light entering from behind the lens and then being reflected off the front side of the lens. Both ghost and flare affect the quality of the image that you see.

Anti-reflective coating improves the light transmission through the lens to nearly 99 per cent and therefore can reduce the effects of ghost and flare substantially.

Anti-reflective coatings can be applied using a variety of different methods, and again PVD is popular. The coating can be made up from compounds such as silicon dioxide (SiO_2), zirconium dioxide (ZrO_2) and aluminium oxide (Al_2O_3). PVD methods allow the coating to be applied in a number of layers and the refractive index and the thickness of each layer can be carefully controlled. Despite the coating consisting of six or more layers, the final thickness of an anti-reflective coating is usually only ~0.2 μm.

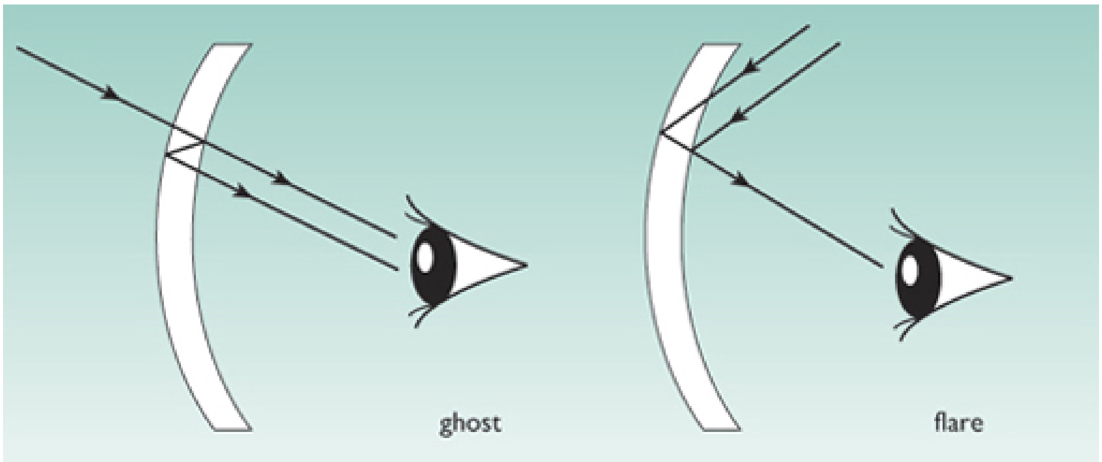


Figure 58 Ghost formation in spectacles

Scratch resistant and anti-reflective coatings on spectacles are an area where there is a highly competitive market, and many of the coatings are carefully patented. Each optician often offers their own version which has a registered trademark associated with it and you will generally find it difficult to find out exactly what treatment your lenses receive!

7.12 Concluding remarks

A bewildering number of surface engineering techniques is available to the modern engineer. How do you decide on the correct process for your particular application? Essentially, an iterative process is required where the application is defined, the properties required are established, the mechanical design of the coating is performed and the correct materials are selected for the required properties. The substrate and interface and surface all need to be engineered to the correct specification, and then finally, the component is coated and the performance evaluated. If you have made the correct choices from the correct specification the final product should be successful.

As you have seen in this part, surface engineering plays an important part in improving the performance of products that are used in your everyday life. Recently, razor blades have become available that use DLC coatings to improve their shaving performance using two mechanisms: reducing the friction coefficient between the skin and the blade and increasing the hardness of the blade edge. These are purposeful choices to engineer the surface of a material to gain a large increase in performance. Surface engineering is an exciting application of technology: look out for its influence next time you choose to buy a product.

SAQ 11

1. What are the advantages of surface engineering a product rather than finding an alternative material? (Use an example from this section to help).
2. Why are ceramics often used as wear-resistant surface coatings for metals? (Look at the data in Appendix 1).

Answer

1. Often an alternative material may not have the necessary property profile (set of properties) required at an acceptable cost. So using stainless steel for car bodies, although possible, is too expensive. Ceramic knives can be made, but they cost far more (at least six times more) than their surface-engineered equivalents.
2. Ceramics are generally much harder than metals, so by engineering a ceramic layer onto a metal's surface, a hard, wear-resistant layer is produced. Bulk ceramics are often too brittle to be used by themselves.

Conclusion

This free course provided an introduction to studying Design. It took you through a series of exercises designed to develop your approach to study and learning at a distance, and helped to improve your confidence as an independent learner.

Appendix I Table of hardness values

Table 3: Typical Vickers hardness numbers for selected materials

Metals	**Vickers hardness number (HV) range from soft to hard**	**Ceramics**	**Vickers hardness number (HV)**	**Polymers**	**Vickers hardness number (HV)**
Tin	5	Limestone	250	Polypropylene	7
Aluminium alloys	25–140	Magnesium oxide	500	PMMA	20
Gold	35	Tungsten carbide	2500	Polycarbonate	14
Copper	40	Titanium nitride	2900	PVC	16
Iron	80	Alumina	2500	Polyacetal	18
Mild steel	140–280	Zirconia	1300	Polystyrene	21
Ferritic stainless steel	170–300	Quartz	1200	CR39	40
Martensitic stainless steel	450–800	Soda-lime silica glass	490	Urea Formaldehyde	41
Ausstenitic stainless steel	180–400	Granite	850	Epoxy	45
Tool steel	700–1000	Silicon nitride	750	Diamond	10,000

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