Chapter 1

Introduction to plastics

Chapter contents

1.1 Introduction

This chapter encourages the reader to familiarize themselves with plastics. It aims to open the reader's eyes to design features in familiar products, and to relate these features to polymer processes. This prepares them for polymer selection exercises in Chapters 13–15. The dismantling exercises can be adapted to suit different courses; for students on a biomaterials course, blood sugar monitors, asthma inhalers, or blood apheresis units can be dismantled. For those on a sports/materials course, the components of a running shoe could be considered (see also further reading). Product examination can be tackled at different levels. The level described here is suitable at the start of a degree course. Later, when most of the topics in the book have been studied, more complex tasks can be tackled – improving the design of an existing product, with reselection of materials and processing route.

There are some polymer identification exercises, using simple equipment. This would make the reader familiar with the appearance of the main plastics. Professional methods of polymer identification, such as differential scanning calorimetry, Fourier transform infrared (FTIR) spectroscopy and optical microscopy, may be dealt with later in degree courses.

This book explores the characteristic properties of polymers and attempts to explain them in terms of microstructure.

1.2 Dismantling consumer products

Using familiar products, the aim is to note component shapes, to see how they are assembled, and measure the variation in thickness. Recycling can also be considered; the ease of dismantling depends on whether the product was intended to be repaired, or to be scrapped if faulty. Screws may be hidden under adhesive labels, and the location of snap-fit parts may be difficult to find.

1.2.1 Plastic kettle

A new plastic kettle can be bought for less than £30, or a discarded one used. Preferably use a cordless kettle, which can be lifted from the powered base. The following four activities can be extended if necessary, by consideration of aesthetics, weight, and ease of filling and pouring.

Briefly touch the kettle's outer surface when the water is boiling

Although the initial temperature of the kettle's outer surface may be 90 °C, the low thermal conductivity of the plastic body compared with that of your finger, means that the skin surface temperature takes more than a minute to reach an equilibrium value, and this value is c. 50 °C. *With a dry finger* touch the kettle's outer surface for less than 5 s. If you have access to a digital thermometer with a fine thermocouple probe, tape the thermocouple to the outer surface of the kettle and check the temperature. What can you deduce about the thermal conductivity of the plastic? Chapter 5 explores the balance between thermal conduction through the plastic and convection from its outer surface.

Measure the thickness of the body at a range of locations

Dismantle the kettle and make a vertical section through the body with a hacksaw. Use callipers to measure the body thickness at a range of locations, and mark the values on the plastic.

Over what range does the thickness vary? Reasons for the nearly constant section thickness are given in Chapter 13. Figure 1.1 shows a typical section. Check how the colouring is achieved. If there is no paint layer on the outside, the colour must be integral (for pigments, www.specialchem4polymer.com).

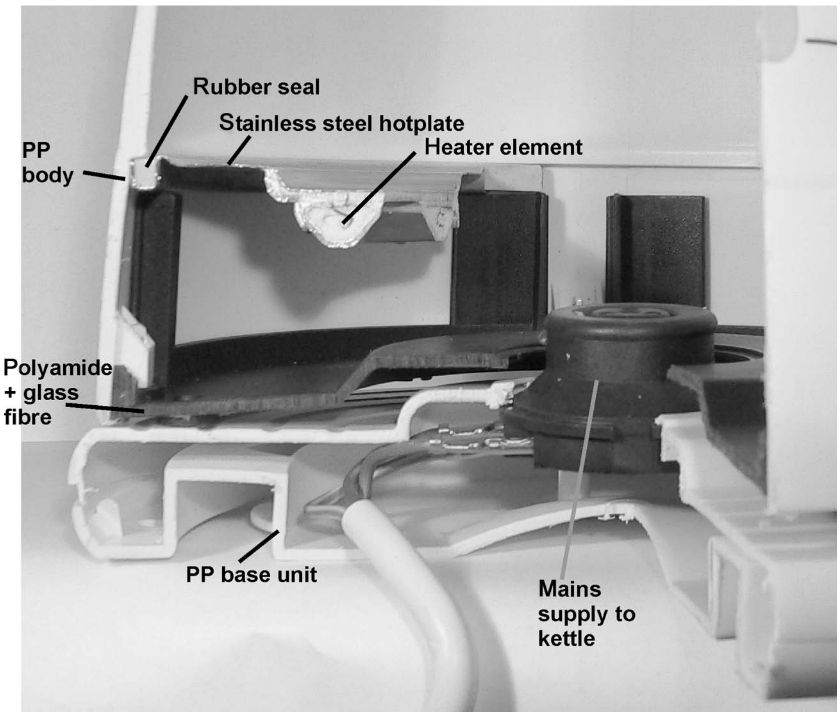


Figure 1.1 Section of a plastic kettle and powered base unit (most of electrical heater was removed from the kettle).

Examine the electrical insulation in the base unit

Note how the electrical conductors are insulated from the parts that are handled. A metal-bodied kettle must have separate insulation wherever mains-connected parts are attached; however plastic is an electrical insulator. Figure 1.1 shows the mains power connections in the base. The coloured insulation (live, neutral and earth) of the braided copper wires is plasticised PVC.

Examine the linking mechanism for the heater switch

Identify the mechanism that connects the on/off switch to the internal contact switch that applies mains power to the heater unit. Identify the thermostat that detects the boiling of the kettle, and note how it switches off the power. Figure 1.2 shows a typical arrangement.

1.2.2 VHS video cassette

Video cassettes are becoming obsolete with the increasing use of DVDs, so one such cassette could be sacrificed.

Check how it has been assembled

Dismantle the cassette by unscrewing the five screws that fasten the two halves together, using a small Phillips-type screwdriver. Lift off the top of the cassette. If there is a clear plastic window, that allows the tape levels to

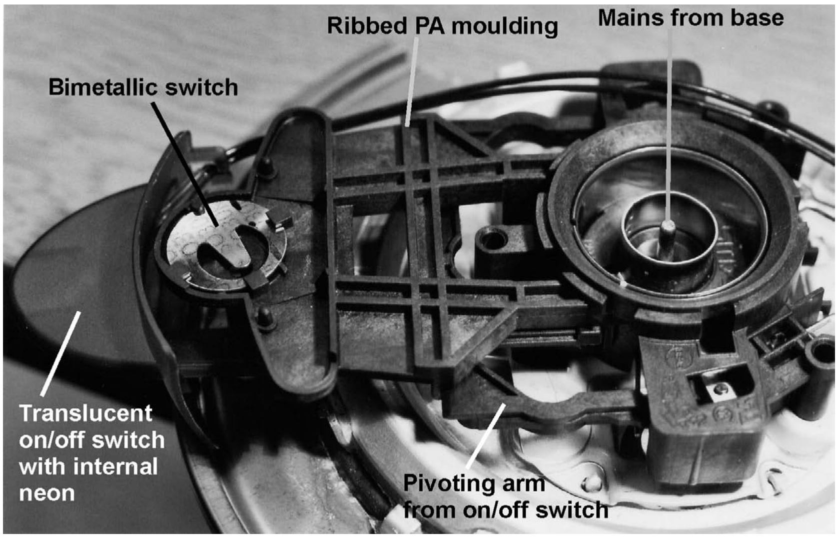


Figure 1.2 Underside of the heater unit inside the kettle, showing the power switch and switch mechanism.

be seen, check how it is attached to the main body. Count the number of parts. After dismantling, see how easy it is to reassemble!

Identify the plastic springs that lock the spools

When a cassette is removed from a recorder, the tape spools are locked to prevent the unwinding of the tape. When it is inside the recorder, a pin presses through a flap at the base of the cassette, causing a lever to operate on two plastic mouldings (Fig. 1.3). They engage with slots in the rim of the tape spools. Check, by pressing with a finger, that the springs can be easily bent. They are made of the engineering thermoplastic polyoxymethylene.

Measure the tensile strength of the tape

Unwind some of the 13 mm wide coated PET tape and measure the thickness (0.02 mm) with callipers. A loop of tape can withstand a tensile force of about 60 N before it yields and about 80 N before it fails in tension. Check this by using a spring balance on a loop of tape, and calculate its tensile strength (approximately 150 MPa). It must bend around cylinders of diameter 5 and 6 mm (Fig. 1.4), so it must have a very low bending stiffness. It must resist wear as it is dragged over the stationary metal cylinders. It must be dimensionally stable, so that the coating is not damaged.

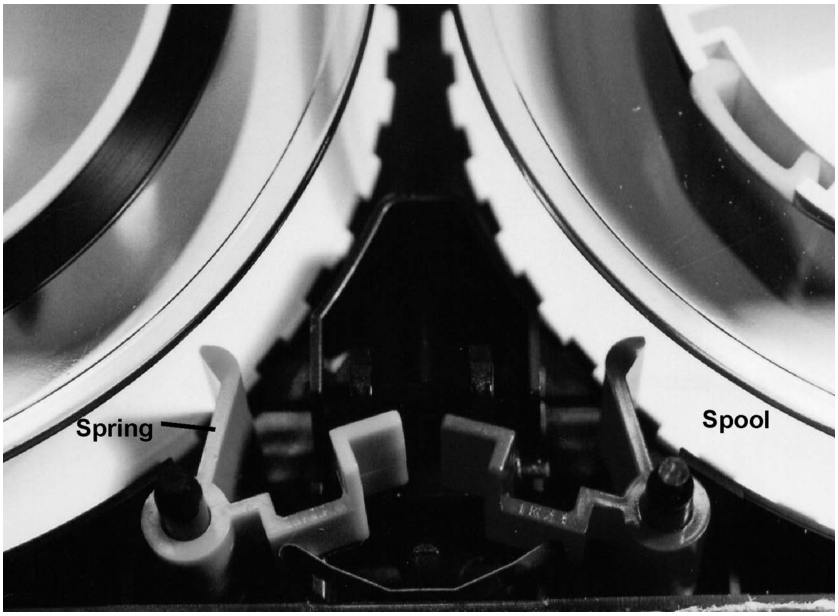


Figure 1.3 Mechanism that locks the spools when the tape is not being played, as seen inside a video cassette.

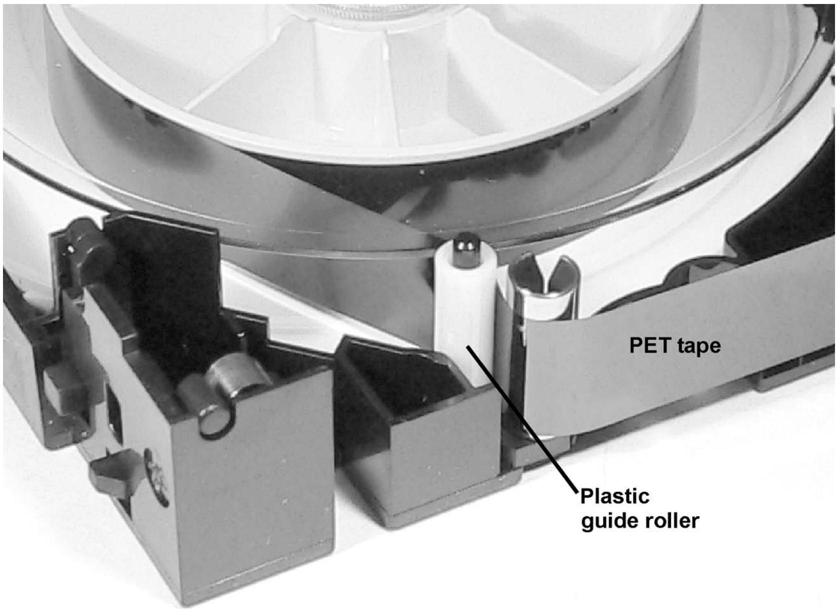


Figure 1.4 PET tape in a VHS cassette passes round a plastic guide roller and a fixed metal cylinder.

1.2.3 Stackable plastic chair

This has a polypropylene (PP) seat, with welded tubular-steel legs. Use a Phillips screwdriver to remove the four screws that attach seat to the legs. These self-tapping screws (Fig. 1.5) with sharp, widely spaced threads, are much longer than the typical 4 mm thick seat. When screwed into a moulded cylindrical boss on the hidden side of the seat, the threads cut grooves in the initially smooth plastic. It is supported by four or more buttresses, to prevent bending loads causing failure, where the boss joins the seat. Measure the thickness of the buttresses.

Note the texture on the upper surface of the chair (Fig. 1.6), whereas the lower surface is smooth. How has this texture been achieved? Is it a reproduction of the mould surface texture, or has it been produced by a post-moulding operation?

1.2.4 Telephone handset

An old handset from an office may be available for dismantling. The numbers for dialling are printed on separate thermoplastic mouldings, each mounted on a domed rubber spring (Fig. 1.7). The domes depress with a click as the side walls buckle, and act as electrical switches. A layer

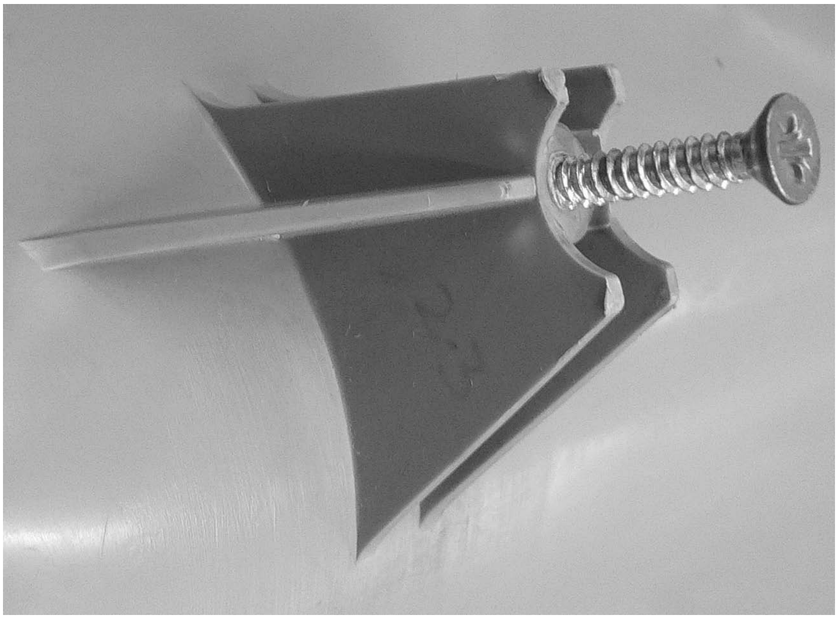


Figure 1.5 Self-tapping screw for attached tubular metal legs, and the boss with buttresses under the seat of a PP stacking chair.

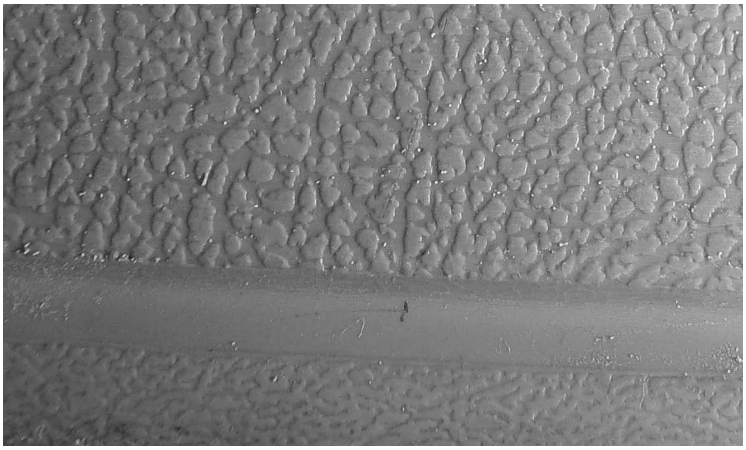


Figure 1.6 Texture on the upper surface of a PP chair.

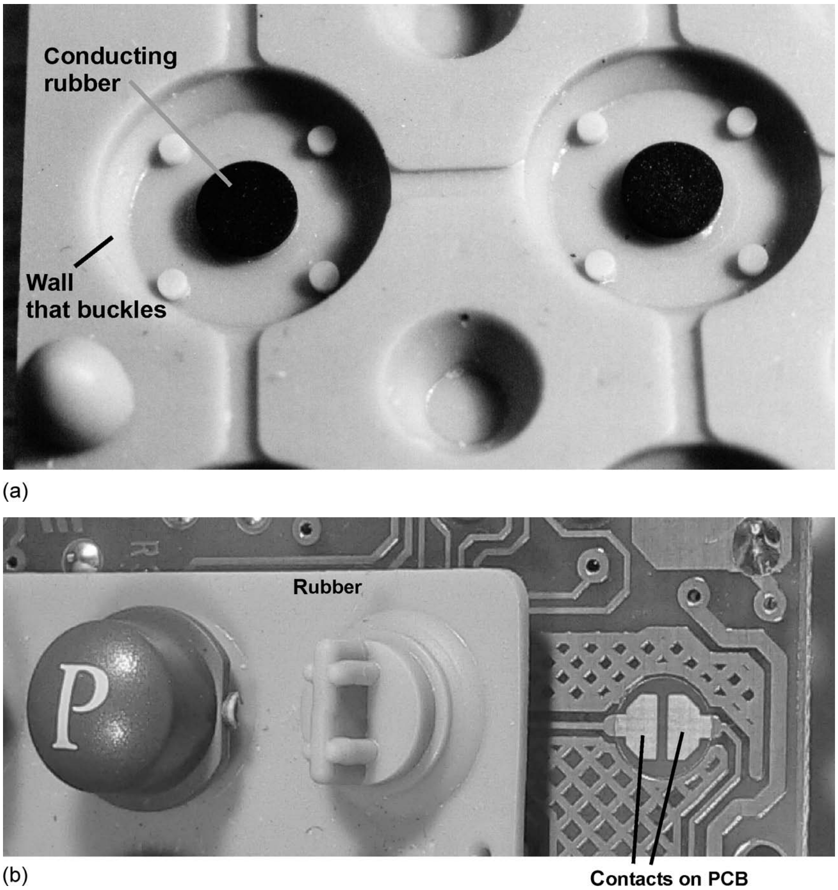


Figure 1.7 Views from both sides of an injection-moulded rubber switch from a telephone.

of carbon-black filled rubber on the base comes into contact with copper tracks on the printed circuit board (PCB). The PCB consists of a polyester resin plus woven fibreglass (GRP) composite, which is also an insulator. The copper tracks on the PCB lead to holes where components are mounted; the PCB must tolerate the temperature of molten solder without distortion.

1.2.5 Summary

Having completed the dismantling exercises, try to add to the following list. *Plastics have advantages over metals of being*

1. self-coloured, by adding about 0.1% of dispersed pigment. There are no painting costs, and the product maintains its colour if scratched.

2. electrical insulators. There is no need for insulating layers between live parts and the body of product, and assembly is simplified.
3. thermal insulators. This conserves energy, and touching a kettle body will not cause scalds.
4. of low density, so lightweight products can be made.
5. impact resistant, with a high yield strain, so thin panels do not dent if locally loaded.

Plastics have advantages over ceramics or glass of being

1. tough, so that the impacts are unlikely to cause brittle fractures.
2. low melting point, so the energy costs for processing are low.
3. capable of being moulded into complex shapes with the required final dimensions (they are 'net-shape', with no final machining stage).

1.3 Mechanical and optical properties of everyday products

Several disposable plastic products are considered, to illustrate mechanical and optical properties.

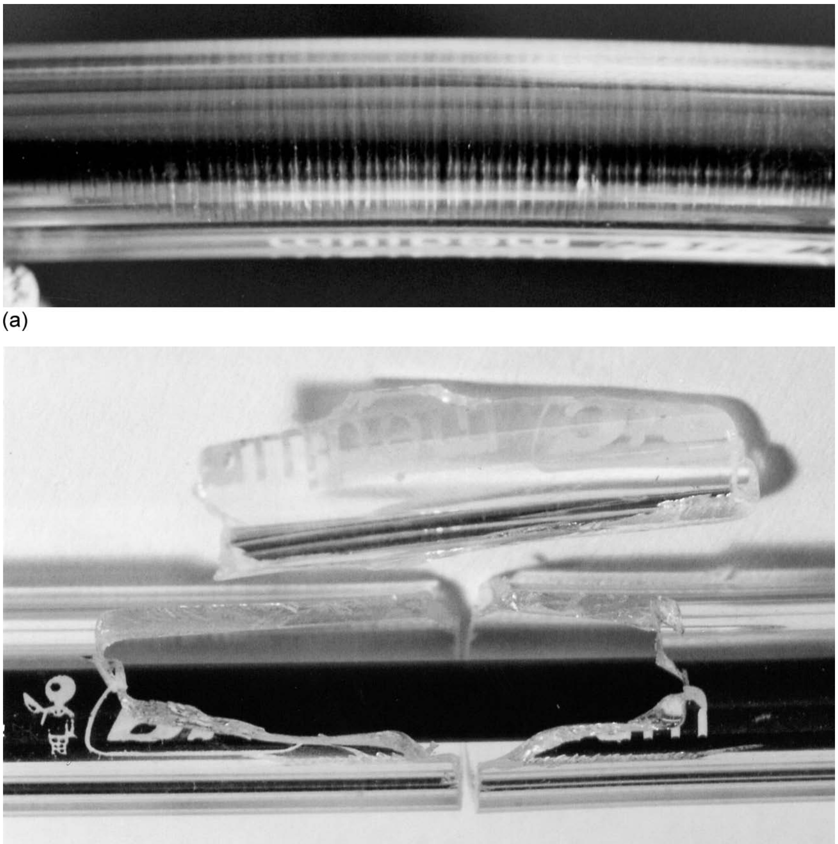
1.3.1 Crazing and fracture of a biro

Find a Bic biro (or a similar ballpoint pen) with a transparent polystyrene body. Hold it up towards a light source and bend it, using the thumbs as the inner and the forefingers as the outer loading points. Make sure that the curved portion is away from you and not aimed at anyone else. Deform the biro by about 10 mm and hold this for about 30 s, then release the load. The biro should return to its original shape, showing that large elastic strains can occur. Tilt the biro against the light and look for parallel reflective planes (Fig. 1.8a). These are called *crazes*.

Continue the loading until the body fractures. Although the ink tube will trap the broken pieces of the body, it is likely that a small piece(s) of PS might detach (Fig. 1.8b). Do not do the experiment without the ink tube, as pieces can fly off at speed. The strain energy released by the fracture is enough to create more than one fracture surface.

1.3.2 Ductile yielding of low-density polyethylene strapping

Low-density polyethylene (LDPE) strapping, cut from 0.42 mm thick film, is used to hold four packs of drink cans together. If pulled slowly with the hands, parts of the strapping undergo tensile necking followed by cold drawing of the thin region (Fig. 1.9). Mark parallel lines at 5 mm intervals



(a)

(b)

Figure 1.8 (a) Crazes in, (b) broken pieces of, a PS Biro after a bending experiment.

across the LDPE before the experiment. Note the extension ratio in the neck, and how the shoulder of the neck moves into the un-necked region.

1.3.3 Optical properties of a CD and polyethylene film

This requires a laser pointer and a CD. Observe safety precautions: do not aim the laser beam at anyone's eyes. Aim it, at approximately normal incidence, at the side of the CD that appears silvered. When the beam hits the tracks near the centre of the disc, a diffraction pattern is created (Fig. 1.10). This pattern is a two-dimensional analogue of X-ray diffraction from a three-dimensional crystal.

If the laser beam hits the main part of the disc, there are just two diffraction peaks, in addition to the directly reflected beam. These are caused by the

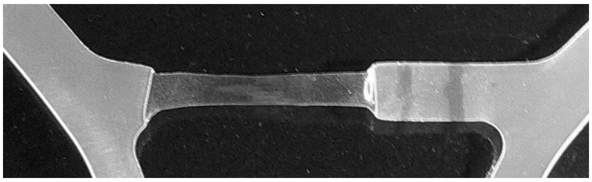


Figure 1.9 Necking and cold drawing of LDPE strapping from a four-pack of drink tins.

Figure 1.10 Diffraction pattern from a laser pointer, when shown on the track near the end of a music CD; the direct reflection has the cross pattern.

regular track spacing in the radial direction. As the circumferential pits are irregularly spaced along each track, this part of the disc acts as a one-dimensional diffraction grating. The diffraction pattern is used to keep the reading head on the track (for more details see Chapter 14). If you scratch off part of the label and the underlying metallized layer, the CD will be transparent in this region. Hence the material, polycarbonate, is transparent.

Macro-bubbles, used inside cardboard boxes for the shock-resistant packaging of goods (Fig. 1.11), are manufactured from 200 mm wide tubular polyethylene film approximately 0.05 mm. The tube is inflated with air then welded at approximately 100 mm intervals. Place a macro-bubble on top of a printed page with a range of font sizes, and note the smallest font size that you can read. High-density polyethylene (HDPE) bubbles scatter

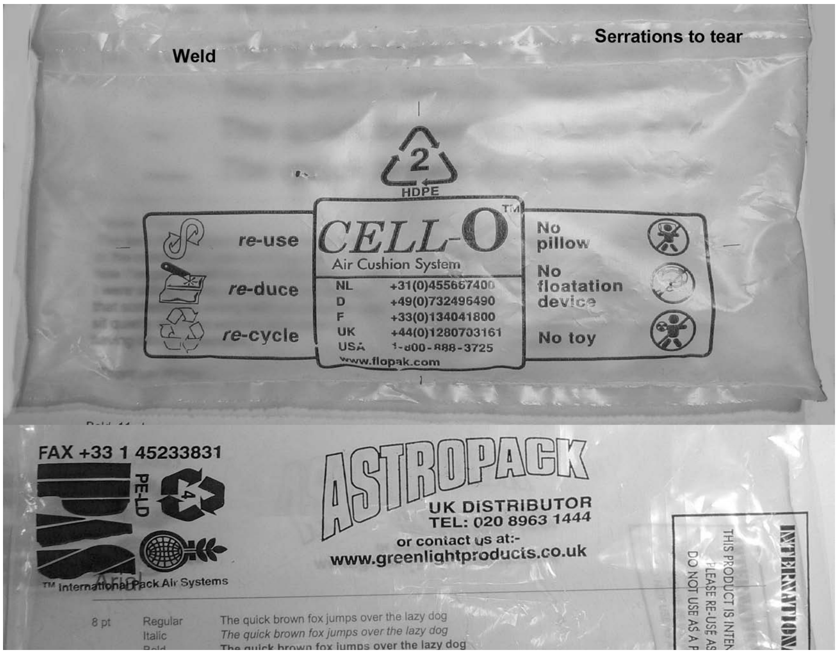


Figure 1.11 LDPE and HDPE macro-bubbles (deflated) on top of a test page with a range of font sizes.

light more than LDPE, so it is more difficult to read the text. If a HDPE bubble is lifted by about 20 mm, it is impossible to read the text.

1.3.4 Degradation of polymers in sunlight

Visit a beach and collect plastic articles that have been there for a couple of years. Apart from foam and hollow air-filled products, there will be polyethylene (PE) or polypropylene (PP) products, which are less dense than water. Note how colours have faded, the surface has become opaque, and the product has started to crack.

1.3.5 Viscoelasticity of a foam bed

Acquire some ‘slow recovery’ foam such as *Confor* (samples are often given away by bedding showrooms). Compress the surface with one hand for a minute, and then observe how long it takes for the indentations in the foam to disappear. Repeat the exercise after the foam has been placed in a refrigerator (5 °C) when it will be much stiffer, or after it has been placed in an oven at 60 °C (when it will be much less stiff and will recover quickly). This shows that the strong viscoelastic response only occurs in a temperature range where the polymer is leathery; close to its glass transition temperature.

1.4 Identifying plastics

Make a collection of food packaging: a milk bottle, a carbonated drink bottle, a supermarket carrier bag, a near-transparent lidded container for food, a margarine container.

Note how plastic bottles have replaced glass for soft drinks, milk, ketchup, etc. One-trip plastic bottles are essential for the sales of bottled water, while they have replaced metal cans for many products. Even containers apparently made from paper (such as Tetrapak) rely on an inner polyethylene layer to protect the paper from the liquid contents.

Use the methods below to identify which plastics are used in one or more products.

1.4.1 Recycling marks

Recycling marks on products (Fig. 1.11) allow the common plastics to be identified (Table 1.1). Sometimes numbers are used in place of the abbreviation for the polymer name.

1.4.2 Product appearance, if unpigmented

Translucent products are semi-crystalline, e.g. PE. Some thin (<1 mm) or highly oriented products appear transparent, in spite of being semi-crystalline (e.g. PET bottles), since the crystals are too small to scatter light. Some thicker PP products appear translucent, but thin mouldings, especially if the PP is nucleated, will appear nearly transparent.

Table 1.1 Recycling marks for polymers

No.	*Legend*	*Polymer*
1	PET	Polyethylene terephthalate
2	HDPE	High-density polyethylene
3	PVC	Polyvinyl chloride
4	LDPE	Low-density polyethylene
5	PP	Polypropylene
6	PS	Polystyrene

Transparent mouldings thicker than 1 mm will be one of the glassy polymers (PVC, PS, PC, etc.). If a thin film of molten, unpigmented plastic is opaque to light it is likely to be filled.

1.4.3 Density

An electronic densitometer can measure the density of small (<10 g) pieces, using Archimedes principle. The pieces are first weighed in air, then again, while suspended in water. Table 1.2 gives the densities and melting points of the main polymers. They are arranged in classes, in order of increasing density. The density of semi-crystalline plastics increases with crystallinity, so a range is given. If a significant amount of a reinforcing or toughening material is added, the density changes, making it more difficult to identify the polymer.

1.4.4 Melting temperatures

Table 1.2 shows the temperature T_m at which the crystalline phase melts, or, for non-crystalline polymers, the glass transition temperature T_g at which the glass changes into a melt. Samples can be dragged across the surface of metal hotplates, set to a range of temperatures. However, when the polymer is just above T_m, some polymers leave a streak of melt, while others of higher viscosity just deform. Therefore, transition temperatures can be overestimated.

1.4.5 Young's modulus

Estimate the order of magnitude of the Young's modulus of a flat part of the product by flexing it. This works best if a standard sized (say 100 mm long, 20 mm wide, 2 mm thick) beam is cut from the product and loaded in three-point bending, since the bending stiffness varies with the cube of the thickness. LDPE is of a much lower Young's modulus (c. 100 MPa) than most other plastics (1–3 GPa), and the surface can be marked with a finger nail.

1.5 Product features related to processing

The aim is to recognise design features associated with processes. The diagrams in Chapter 5 show the major processes. Both the product shape and surface marks provide clues for process identification.

Table 1.2 Polymer densities and transition temperatures

Abbreviations	*Polymer*	*Density* ($kg\,m^{-3}$)	T_g (°C)	T_m (°C)	*Event if bent through 90°*
Semi-crystalline plastics					
P4MP	Poly (4-methyl-pentene-1)	830	25	238	Semi-brittle
PP	Polypropylene	900–910	−10	170	Whitens
LDPE	Low-density polyethylene	920–925	−120	120	Ductile
MDPE	Medium density polyethylene	935–945	−120	130	Ductile
HDPE	High-density polyethylene	955–965	−120	140	Ductile
PA 6	Polyamide 6	1120–1150	50	228	Ductile
PA 66	Polyamide 6,6	1130–1160	57	265	Ductile
PET	Polyethylene terephthalate	1336–1340	80	260	Ductile
POM	Polyoxymethylene (Acetal)	1410	−85	170	Semi-brittle
PVDC	Polyvinylidene chloride	1750	−18	205	
PTFE	Polytetrafluoro ethylene	2200	−73	332	Ductile
Glassy plastics					
PS	Polystyrene	1050	100		Brittle
SAN	Styrene acrylonitrile copolymer	1080	100		
ABS	Acrylonitrile butadiene styrene copolymer	990–1100	100		Whitens
PC	Polycarbonate	1200	145		Ductile
PVCu	Polyvinyl chloride unplasticised	1410	80		Ductile
PMMA	Polymethyl methacrylate	1190	105		Brittle

T_m, crystal melting temperature; T_g, glass transition temperature.

1.5.1 Blow mouldings

These are hollow containers, usually with an opening of smaller diameter than the body. Both ends of the moulding may be cut off to produce a tubular product, or one end cut off for a bucket-shaped container. The wall thickness varies with position, and there is a weld line across the closed end of the container (Fig. 1.12). Sometimes near-parallel lines are visible on the inner surface. These indicate the extrusion direction when the parison (tubular preform) emerged from a die. Look for the weld location on the base of an HDPE milk bottle; this aligns with the external surface line from the mould split. Section the milk bottle vertically, in a plane perpendicular to the weld line, and measure the thickness at the weld line compared with elsewhere. Note the threads in the neck are corrugated.

Stiff HDPE tool boxes can be created by allowing the two sides of the blow moulding to come into contact at some locations and form welds (Fig. 1.13). The 0.4 mm thick hinge region is created by pressing the HDPE with metal bars, and the 'click shut' catches are also part of the blow moulding.

1.5.2 Extruded products

These have a constant cross section. Examples are domestic gutters or down-pipe, or (replacement) window frames, made from PVC. Look through a length of an extrusion, towards a window, for markings parallel to the extrusion direction, which have come from the die. The outer surface is in contact with a sizing die, whereas the inner surface cools in air and can

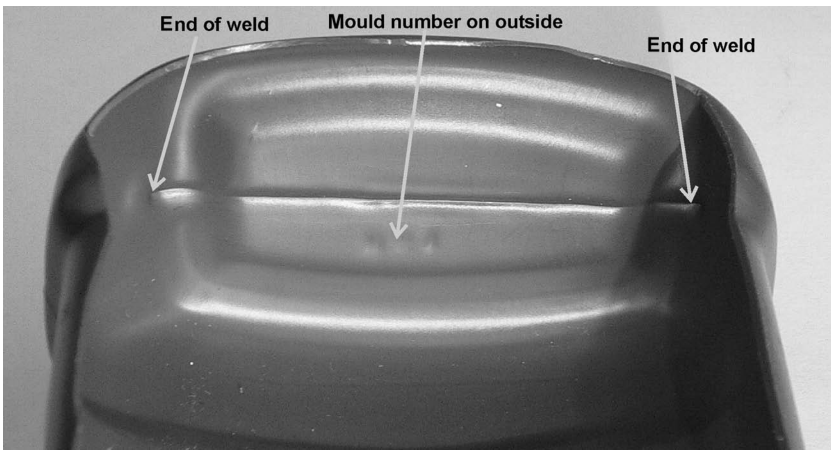


Figure 1.12 Sectioned blow-moulded bottle, showing the weld line at the base.

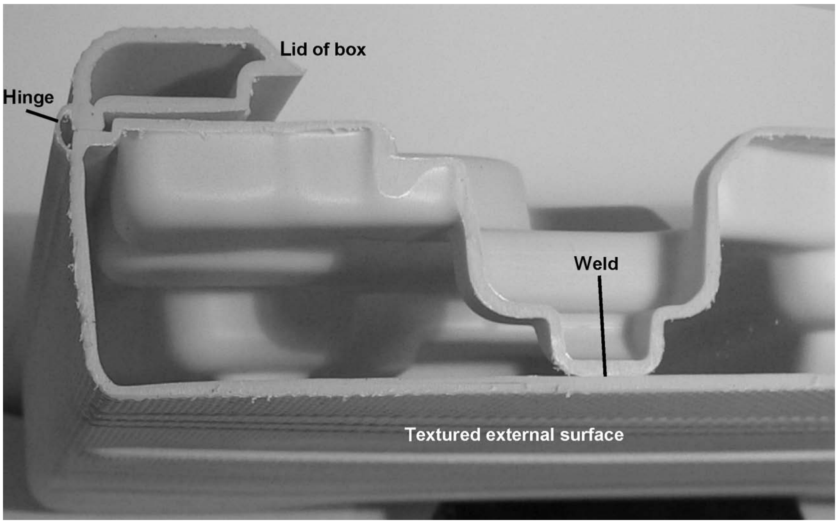


Figure 1.13 Section through a blow-moulded HDPE tool box (45 mm thick). Both lid and base of the box are hollow, with reinforcing welds at intervals interior.

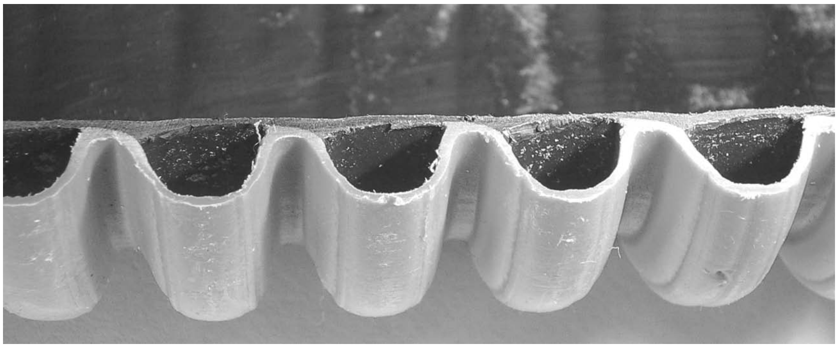


Figure 1.14 Extruded HDPE pipe, with corrugations at 18 mm intervals in the outer layer, for buried electric cables.

change shape slightly. The pipe wall provides the bending stiffness and resistance against weathering. Pipes for cable TV in the UK are green with a corrugated exterior, but a smooth inner wall. Figure 1.14 shows a pipe for electrical cable, with an outer red corrugated layer bonded to a smooth inner black layer (details of the process are shown in Fig. 13.2). Such pipes offer maximum resistance to crushing by soil loads for a given weight of polymer.

1.5.3 Injection mouldings

Injection mouldings can contain T-junctions (where *ribs* meet a surface) and holes. Figures 1.1–1.7 show injection moulded parts. The point where the *sprue*, which feeds the melt into the mould cavity, has been removed should be visible as a slightly rough, often circular region. On the concave side of the product, circular surface marks indicate the location of *ejector pins*, which push the cold moulding from the mould. Figure 1.15 of a moulded box, shows the ejector pin marks on the inside of the box, and a moulded-in hinge between the two halves.

Consider the polypropylene seat of a stackable chair. The seat sides are 'bent over', providing a place to grip the seat. These sides provide bending stiffness to the seat. You can prove this if you can cut off the side parts; if you lean back in the chair, it flexes excessively at the back/seat junction. There is more about the bending creep of plastics in Chapter 7 and the bending stiffness of beams in Chapter 13. The seat surface has a moulded-in texture (Fig. 1.5), to increase the coefficient of friction with your clothes, and to disguise scratches. Note how dust build-up and scratches spoil the appearance of the hidden side, which is smooth.

1.5.4 Thermoformed products

These tend to be curved panels, or shallow containers. They have a variable thickness, since only the convex side contacts a metal die. They can be as thin as 0.1 mm, since a sheet of melt is stretched before contact with the cold mould, or as thick as 10 mm. There will be no signs of any injection point or ejector pins. Typical examples are disposable coffee cups (Fig. 1.16a), margarine containers, baths and shower trays.

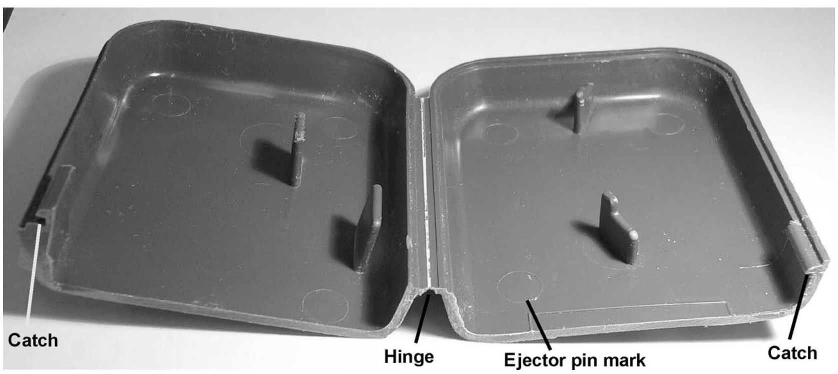


Figure 1.15 Section through an injection-moulded PP box for a micrometer. The moulded-in hinge has whitened in use.

(a) (b)

Figure 1.16 Section through a thermoformed PS disposable coffee cup, with shallow corrugations in the 0.2 mm thick sidewall. The corrugations were outlined in felt-tip then the cup heat reverted to 0.8 mm thick sheet.

Use a sharp pair of scissors to cut a section through the cup, and note the corrugations which increase the bending stiffness of the wall. The corrugations also provide grip and reduce heat transfer to the fingers. Note the variation in wall thickness.

Either use a hot air blower (for paint stripping), or put the cup on a layer of aluminium foil in an oven at 120 °C and note the gradual shape reversion to a nearly-flat sheet (Fig. 1.16b). The thermoforming process involved the elastic stretching of a sheet of polymer melt, and this orientation was frozen into the cup when it cooled. On reheating, the plastic attempts to return to its original shape.

1.5.5 Blown film

The blown film process creates a continuous tube of film, usually less than 0.25 mm thick, which is flattened and rolled up. It can be cut into lengths and welded to produce products such as supermarket carrier bags or protective bubbles (Fig. 1.11). For a carrier bag, determine where the film has been welded and where it has been cut, or folded. Support the handles on a spring balance, then use sand (or tins) as the loading medium and determine the tensile strength of the polyethylene in the handle region.

Figure 1.17 Details of the neck region of an injection-blow moulded PET bottle. The bottle on the left has been heat treated at 120 °C, while the neck of a preform is shown on the right.

1.5.6 Injection-blow moulded bottles

Compare a PET carbonated drink bottle with an HDPE milk bottle. The moulded neck threads of the PET bottle (Fig. 1.17) have T-sections. The internal pressure of 4 bar in the carbonated drink bottle can only be resisted by a lightweight bottle if the polymer is oriented to increase its strength. However, the milk bottle is under no internal pressure, so a lower cost material (HDPE) and process can be used. Gas diffusion is covered in Chapter 11, while the stress analysis of a pressure vessel is covered in Appendix C. Note the location of the injection sprue in the centre of the base of the PET bottle. Try placing an empty PET bottle in an oven at 120 °C for 1 h. Note how it shrinks both in length and diameter, showing that the PET had been biaxially oriented. The base and the neck become milky in appearance, due to the crystallisation of these initially amorphous regions. The shrinkage in these regions is relatively low. The main part of the bottle remains clear, since it was already semi-crystalline.

1.6 Summary

Hopefully you are now familiar with the appearance and some typical properties of the commodity thermoplastics, and can recognise how some products have been made. You are now ready to study the microstructure and processing of polymers in more detail, and to find out how the properties can be related to the microstructure.