

# Chapter 22

## Resin-based Filling Materials

### 22.1 Introduction

The development of filling materials based on synthetic polymers has been initiated by two major driving forces, in addition to the obvious commercial ones. Firstly, there was a requirement to produce a material which could overcome the major deficiencies of the silicate materials, namely, erosion, brittleness, acidity and a moisture sensitivity which demanded very careful manipulation. Secondly, developments in polymer technology produced resins which could be readily cured at mouth temperature and, with the aid of pigments and fillers, could be made to resemble the natural tooth in appearance.

The first materials to be widely used were the *acrylic resins*. These are, essentially, similar to resins used in denture construction (Chapter 13). The unfilled acrylic resins have now been superseded by a myriad of *composite materials* consisting of a heterogeneous blend of organic resin and inorganic filler.

### 22.2 Acrylic resins

These are supplied as a powder and liquid which are mixed together. The composition is similar to that given in Table 13.1 for denture base materials. Briefly, the materials consist of a powder and liquid. The powder contains beads of polymethylmethacrylate (<50  $\mu\text{m}$ ), chemical initiator (often a peroxide) and pigment, whilst the liquid consists of methylmethacrylate monomer and a chemical activator (often a tertiary amine). The pigments used are, generally, white, yellow or brown, in order to match natural tooth shades, as opposed to the pink pigments used in denture base polymers. The setting reaction involves a free radical addition polymerisation as described in Chapter 12.

The amine which is often used as a chemical activator in acrylic resins remains largely unconsumed at the end of the setting reaction. One such amine which has been widely used is *N, N'* dimethyl-*p*-toluidine. This has very poor colour stability, particularly in ultraviolet light, and gradually changes from clear to brown, causing a consequent change of colour in the material itself; hence some acrylic filling materials have been reported as having very poor colour stability. Attempts to overcome this problem have involved the use of UV absorbers and more stable amines as well as other types of activators and initiators. Peroxide/alkylborane systems have been used as an alternative to peroxide/amine. This system was claimed to produce a material with adhesive properties although this has never been extensively evaluated.

Other materials utilized a peroxide/mercaptan initiation system whilst peroxide/sulphinic acid was used in other products. The latter system is complicated because the sulphinic acid (normally *p*-toluene sulphinic acid) is unstable and can inadvertently cause premature polymerisation of the monomer if incorporated in the liquid. This problem is overcome by incorporation of a salt of the sulphinic acid in the powder with the peroxide. A small quantity of methacrylic acid is incorporated in the liquid. This rapidly converts and sulphinic acid salt to the free acid when powder and liquid are mixed together. The sulphinic acid then reacts with the peroxide to activate the polymerisation process.

*Advantages:* The acrylic resin materials are *less prone to erosion* than silicates. They have low solubility over a wide range of pH values. They are *less acidic* than silicates though cannot be considered biologically bland due to the presence

of residual methylmethacrylate monomer. They are *less brittle* than silicates although their mechanical properties are far from ideal.

The materials are good thermal insulators having a *low value of thermal diffusivity*,  $1.0 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$  as opposed to  $2.0 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$  for dentine. The ability to match the appearance of tooth substance is, initially, very good, although some products have a tendency to discolour gradually with time. Discoloration at the margins is also observed with many restorations.

*Disadvantages:* Although the acrylic materials do not contain any strong acids, some products contain methacrylic acid, used to modify setting characteristics, and all contain a certain level of residual methylmethacrylate monomer which is *irritant*. This, coupled with a significant *temperature rise* during setting caused by a highly exothermic polymerisation reaction, necessitates the use of a protective cavity base material. The material of choice is a setting calcium hydroxide type. Products containing eugenol should be avoided since they retard the setting of the resin and cause discoloration.

The materials undergo a considerable *setting contraction* (6% by volume). If uncontrolled, this could produce a significant marginal gap down which fluids could penetrate. The problem may be partially alleviated by filling the cavity with small increments and allowing the contraction to occur towards the walls of the cavity before the next increment is added. Another approach is to over-fill the cavity and place the setting material under strong finger pressure with a matrix strip during setting.

The *coefficient of thermal expansion* value for acrylic resin is some ten times greater than that for tooth substance (see Table 22.2). The potential for *percolation* of fluids down the restoration–tooth interface when the patient takes hot or cold food and drink is, therefore, significant.

The mechanical properties of acrylic resin compare unfavourably with those of the natural tooth material which it replaces (Table 22.1). The low value of *modulus of elasticity* indicates that acrylic resin is a far more flexible material than either enamel or dentine. Flexing of restorations under load can lead to marginal breakdown. The lower *compressive strength* and *hardness* values of acrylic resin are reflected in a *poor durability*, particularly when restorations are subjected to abrasive forces. Material loss by *wear* is a phenomenon associated with these relatively soft materials.

*Current status:* Acrylic resins are now rarely used as permanent filling materials. They overcome the major problems associated with silicates but have many other disadvantages which preclude regular use. The materials are still in use for temporary crown and bridge construction.

### 22.3 Composite materials – introduction

A composite material is a product which consists of at least two distinct phases normally formed by blending together components having different structures and properties. The purpose of this is to produce a material having properties which could not be achieved from any of the individual components alone. The two main components of composite filling materials are the resin phase and the reinforcing filler. The beneficial properties contributed by the resin are the ability to be moulded at ambient temperatures coupled with setting by polymerisation achieved in a conveniently short time. The disadvantages of using resin alone have been given in the previous section. The beneficial properties contributed by the filler are rigidity, hardness, strength and a lower value for the coefficient of thermal expansion. In addition, if the filler occupies a significant proportion of the volume of a composite material it markedly lowers setting contraction. The effect of filler

**Table 22.1** Some mechanical properties of acrylic resin, enamel and dentine.

	Acrylic resin	Enamel	Dentine
Modulus of elasticity (GPa)	2	50	15
Compressive strength (MPa)	70	250	280
Tensile strength (MPa)	30	35*	40–260**
Hardness (Vickers)	20	350	60

\* diametral test, \*\* higher values from flexural test.



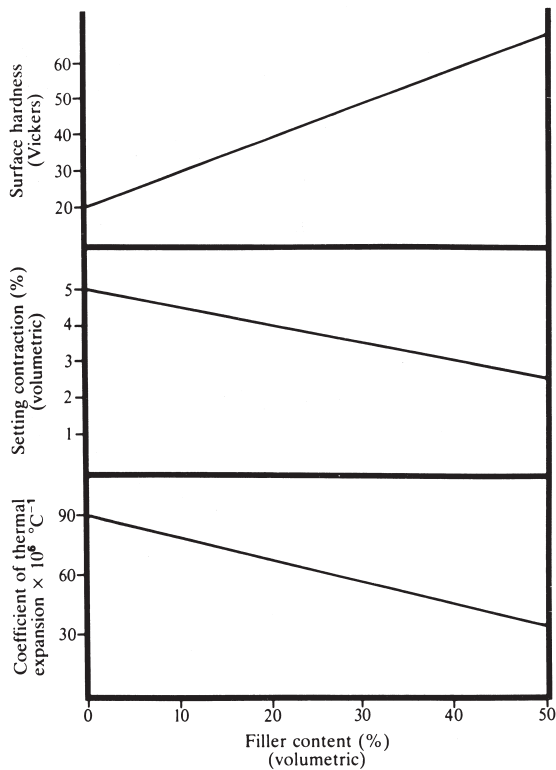


Fig. 22.1 Variation of surface hardness, setting contraction and coefficient of thermal expansion with inorganic filler content for acrylic resins.

depends on the type, shape, size and amount of filler incorporated and, often, the existence of efficient coupling between the filler and resin.

When particulate glass fillers are incorporated in acrylic resins, three properties, namely, coefficient of thermal expansion, setting contraction and surface hardness, depend almost linearly on the filler content, as shown in Fig. 22.1.

Other thermal and mechanical properties may vary in a similar way. Strength and modulus of elasticity generally increase with addition of filler, as does abrasion resistance, probably as a result of increased surface hardness. If the added filler is translucent, the optical properties of the resin are improved and a more lifelike appearance produced.

The resins used in composite materials are invariably based in methacrylate monomers. Simple methylmethacrylate was used in some early products but most materials now utilize dimethacrylates. These monomers undergo a smaller contraction on setting and form a highly cross-linked three dimensional network with properties

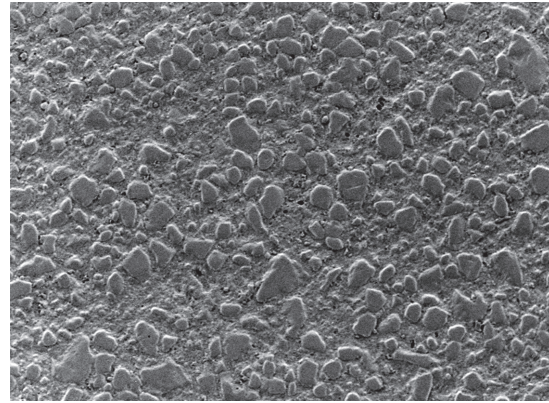


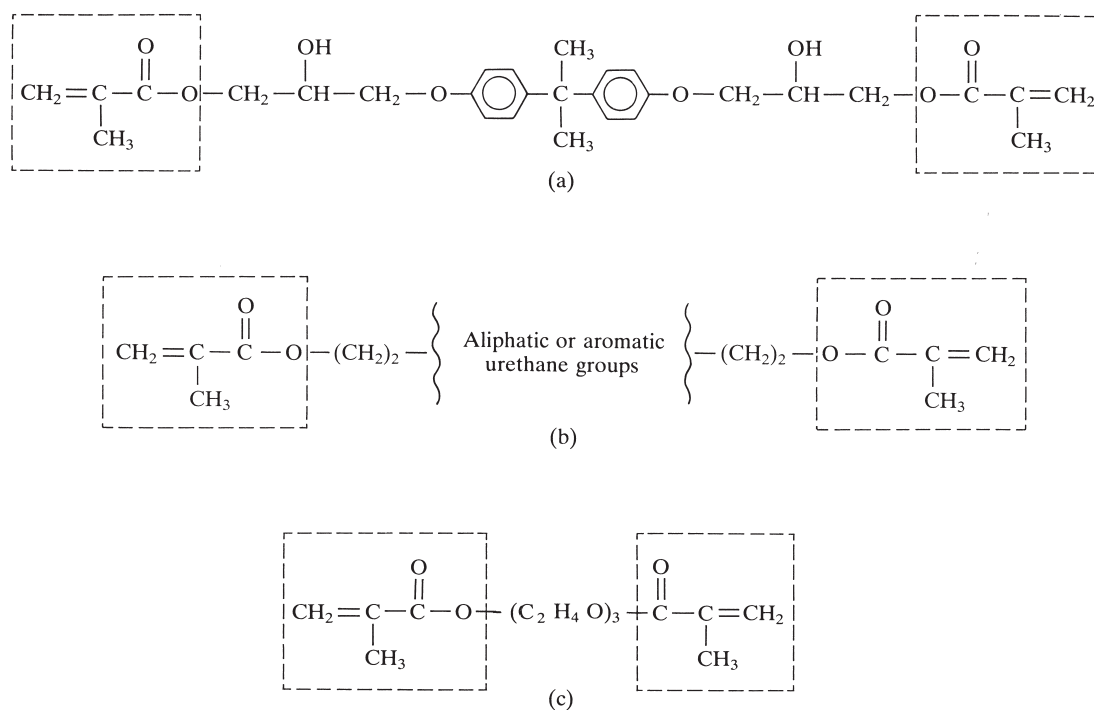
Fig. 22.2 Polished surface of a dental composite showing filler particles embedded in a matrix of resin ( $\times 1445$ ).

which are generally better than those of polymethylmethacrylate.

## 22.4 Classification and composition of composites

All dental composites consist of a blend of resin and inorganic filler. Methods used to characterise materials are based upon the method used to activate polymerisation of the resin and on the particle size distribution of filler. Figure 22.2 shows the polished surface of a composite in which the filler particles embedded in a matrix of resin are clearly visible.

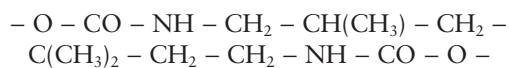
*Resins:* The nature of the resin may alter slightly from one product to another, although, essentially, they all contain a modified methacrylate or acrylate. Figure 22.3 gives the molecular structures of two of the most commonly used monomers, Bis GMA and urethane dimethacrylate, together with that of tri-ethylene glycol dimethacrylate (TEGMA) which is a comonomer often used to control the viscosity of the unmixed materials. It can be seen from Fig. 22.3 that the monomer and comonomer molecules are difunctional methacrylates. Each carbon-carbon double bond is able to take part in a free radical addition polymerisation, to give a highly cross-linked resin after setting. New composites, only just appearing on the market, are based upon a different kind of chemistry in which polymerisation occurs through a ring-opening mechanism. These products are considered in the context of the reduction in setting contraction (see page 207).



**Fig. 22.3** Molecular structures of three modified methacrylate or acrylate resin monomers used in composite materials. (a) Bis GMA (addition product of BisPhenol A and glycidylmethacrylate). (b) Urethane dimethacrylate. (c) Triethylene glycol dimethacrylate.

Bis GMA is a difunctional methacrylate which is normally formed by a reaction between bisphenol A and glycidylmethacrylate. It has two phenyl groups which lend a degree of rigidity to the molecule and the hydroxyl groups are thought to give some intermolecular hydrogen bonding. These features give Bis GMA a consistency which is similar to that of thick treacle at room temperature. Blending of filler particles with a material of this consistency is difficult and the manufacturers normally have to use a fluid diluent monomer such as TEGMA to reduce the viscosity. A mixture of three parts Bis GMA and one part TEGMA is typically blended with filler. Bis MA monomer is used in some products. This is very similar to Bis GMA but contains no hydroxyl groups.

The urethanedimethacrylate monomers may be aliphatic or aromatic in nature. The central group in Fig. 22.3 is typically:



in a commonly used aliphatic dimethacrylate monomer. Monomers of this type have relatively low viscosity and do not require the use of a diluent monomer although some manufacturers do blend various monomers together. Urethanedimethacrylate monomers containing aromatic groups have a slightly more complicated structure and are often more viscous, normally requiring the presence of a diluent monomer.

The size of the monomer and comonomer molecules, coupled with a rapid increase in viscosity during setting, causes a relatively high concentration of acrylate or methacrylate groups to remain unreacted after setting. This results from the fact that reactive methacrylate groups find it increasingly difficult to migrate to the reaction sites as viscosity increases. When the glass transition temperature of the polymerizing mass approaches the ambient temperature the rate of diffusion diminishes markedly and little further reaction is possible. Further reaction could be encouraged by heating the material to a temperature well above

the ambient temperature in order to regenerate mobility of reactive groups. Heat treatment of this type is not feasible for direct composite filling materials but may be used to enhance the properties of composite inlay materials.

**Methods of activation:** Polymerisation may be activated *chemically*, by mixing two components, one of which typically contains an initiator and the other an activator, or by an external *ultraviolet* or *visible light* source. The traditional method for delivering the blue visible light required for 'visible light activation' involves the use of a quartz tungsten halogen (QTH) lamp. Other systems including plasma arc, laser and light emitting diode (LED) systems are now also available. These various types of lamps are discussed on p. 204.

For chemical activation, many different methods of dispensation are available. The most popular is the 'two paste' system (see Fig. 22.4). Each paste contains a blend of resin and filler. One paste contains about 1% of a peroxide initiator, such as benzoyl peroxide, whilst the other paste contains about 0.5% of a tertiary amine activator, such as *N, N'* dimethyl-*p*-toluidine or *p*-tolyl diethanolamine. The ensuing reaction is a free radical addition polymerisation as described in Chapter 12.

Other systems which rely on chemical activation are as follows:

- (1) Powder/liquid systems, in which the powder contains filler particles and peroxide initiator whilst the liquid contains monomer, comonomer and chemical activator.



**Fig. 22.4** A typical two paste composite material. Approximately equal amounts of two pastes are taken out of the containers using a plastic spatula and then they are mixed together on a paper pad.

- (2) Paste/liquid materials in which the paste contains monomers, comonomers, filler and peroxide whilst the liquid contains monomers and chemical activator.
- (3) Encapsulated materials in which the filler, mixed with peroxide, is initially separated within a capsule from the monomers and comonomers containing the chemical activator. On breaking the seal between the two parts of the capsule the reactive components come into contact and are mixed mechanically.

*Light-activated* materials are generally supplied as a single paste which contains monomers, comonomers, filler and an initiator which is unstable in the presence of either ultraviolet (UV) or high-intensity visible light. For UV-activated materials, the most commonly used initiator is benzoin methyl ether. At certain selected wavelengths within the UV range, this molecule is able to absorb radiation and undergo heterolytic decomposition to form free radicals. The radicals initiate polymerisation which then continues in much the same way as that described for vinyl monomers (p. 102).

The use of UV-activated materials has diminished greatly since the possible dangers of long-term exposure to ultraviolet radiation were highlighted.

For visible light-activated materials the initiator system comprises a mixture of a diketone and an amine. Camphorquinone is a commonly used diketone which rapidly forms free radicals in the presence of an amine and radiation of the correct wavelength and intensity.

Light-activated materials require the use of a specialist light source, capable of delivering radiation with the appropriate characteristics to the surface of the freshly placed material *in situ*. (see Fig. 22.5)

Care must be taken in the storage of unused pastes since exposure to sunlight, or particularly to the surgery operating light, may be sufficient to activate a slow initiation process which causes the paste to thicken and become unworkable. For materials which are supplied in pots it is essential to replace the lid quickly after removing the required amount of paste.

Many materials are supplied in syringes which will enable the operator or his assistant to expel sufficient material for one restoration. The



**Fig. 22.5** Light-activated composite materials are often provided in light-proof syringes of the type shown here. Materials are provided in various tooth shades corresponding to the different shades on the shade guide which is also shown in this figure. The same manufacturer is likely to also supply a light curing unit which is used to activate polymerisation. The curing units shown here are a QTH unit (on the right) and an LED unit (on the left).

material remaining in the syringe is not exposed. Another method of dispensation is in the form of 'compules'. Each compule contains sufficient paste for at least one restoration and is extruded into the cavity by placing the compule into a press. (see Fig. 22.6)

**Fillers:** The type, concentration, particle size and particle size distribution of the filler used in a composite material are major factors controlling properties.

Fillers commonly used include quartz, fused silica and many types of glass including aluminosilicates and borosilicates, some containing barium oxide.

The first generation of composite materials typically contain 60–80%, by weight, of quartz or glass in the particle size range of 1–50  $\mu\text{m}$ . The particle size distribution may vary, within this range, from one product to another, some containing relatively greater amounts of larger particles, approaching 50  $\mu\text{m}$ , others containing larger



**Fig. 22.6** This shows the three most common means of supplying composite filling materials. On the left we have the two paste chemically activated materials supplied in pots. Mixing of the pastes is required to bring about activation of polymerisation. In the middle we see the syringe format and on the right we see mini-syringe or 'compule' format. Both the syringe and compule format are used for light-activated materials which require no mixing. In the case of the compule format each small mini-syringe contains sufficient material for one or two restorations and the compule is disposed of after use.

quantities of smaller particles. Materials containing filler particles of this type are normally referred to as *conventional* composites. The filler particles are subjected to a special pretreatment prior to blending with the resin. This involves laying down a surface coating of a *coupling agent* on the particles to enhance bonding between the filler and resin matrix. The coupling agent most commonly used is  $\gamma$ -methacryloxypropyltrimethoxysilane:



This is a difunctional molecule which at one end has the characteristics of a methacrylate monomer whilst at the other it has a silane group capable of interacting and bonding with glass or quartz surfaces. Hence, it is able to set up a bond between the resin and filler components in a composite system.

Since the composite filling materials were introduced in the mid-1960s, there has been a trend towards the use of fillers with smaller particle size. Many of the currently available products with glass or quartz fillers contain particles in the more limited range of 1–5  $\mu\text{m}$ .

Another development has been the introduction of a number of products containing submicron



particles of silica. These materials are referred to as *microfilled composites* and contain silica particles in the range 0.01–0.1  $\mu\text{m}$  with a typical mean diameter of 0.04  $\mu\text{m}$ . The very small particle size produces a massive increase in available surface area for a given volume of filler (typically  $10^3$ – $10^4$  times more surface area). Consequently, it is not possible to incorporate very high filler loadings of this small particle size and products which are available contain only 30–60% filler by weight. Even at these lower levels, calculations show that many filler particles must be present as agglomerates and not as individual particles surrounded by resin.

The method of incorporating the smaller particles varies, direct blending with resin being difficult. The most widely used method is to prepare prepolymerised blocks of resin containing a high filler loading of silica. The block is splintered and ground to give particles of resin up to 100  $\mu\text{m}$  in diameter, each containing silica. These particles are blended with monomer, comonomers, initiators or activators to form pastes.

A third series of composite materials contain a blend of both conventional glass or quartz particles together with some submicron, particulate silica. These products are referred to as *hybrid composites*. Using filler loadings of about 75% conventional size (1–50  $\mu\text{m}$ ) and 8% submicron size (0.04  $\mu\text{m}$  average), a total filler content of 83% or greater can be achieved. Some hybrid products contain a blend of at least three different particles sizes of filler. These allow efficient packing of filler into the smallest possible volume and enable filler loadings of up to 90% by weight to be achieved.

Figure 22.7 shows diagrammatically the microstructure of the main groups of materials.

Modern formulations of composites often involve new methods of manufacture of fillers in

which the particle size and shape is controlled and in which the traditional boundaries between conventional, microfilled and hybrid products can no longer be clearly identified. Wet techniques including sol-gel technology as well as jet blasting techniques in which streams of powder are fired at other streams to reduce and control particle size and shape give the manufacturer the opportunity to optimize all aspects of filler composition and nature. Composites produced using very small particles of less than one  $\mu\text{m}$  average diameter are often termed ‘nanocomposites’ by manufacturers. However, the essential characteristics of such materials are adequately defined within the groups of microfilled and hybrid materials without the need to consider a whole new class of products.

Conventional, microfilled and hybrid composites are all available as either chemically activated or light-activated products.

The ISO Standard for resin-based restorative materials (ISO 4049) classifies materials as being of two types depending upon the intended application. Type 1 is claimed by the manufacturer to be suitable for the restoration of cavities involving occlusal surfaces. Type 2 includes all other polymer-based filling and restorative materials. The standard further sub-divides materials into three classes as follows:

- Class 1 comprises self-curing materials whose setting is activated by mixing an initiator and an activator.
- Class 2 materials are those whose setting is effected by application of energy from an external source such as blue light or heat. These materials are further sub-divided as follows:

Class 2 group 1 – materials whose use requires the energy to be applied intra-orally.

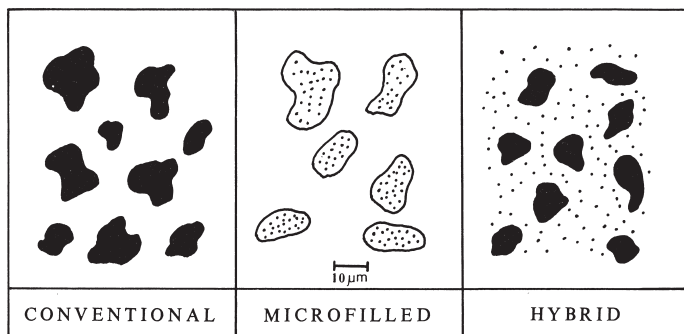


Fig. 22.7 Diagrammatic representation of the size of filler particles used in the three main groups of composite resins. A further group of ‘nanocomposites’ have particles similar to those used in microfilled products.

Class 2 group 2 – materials whose method of use requires the energy to be applied extra-orally.

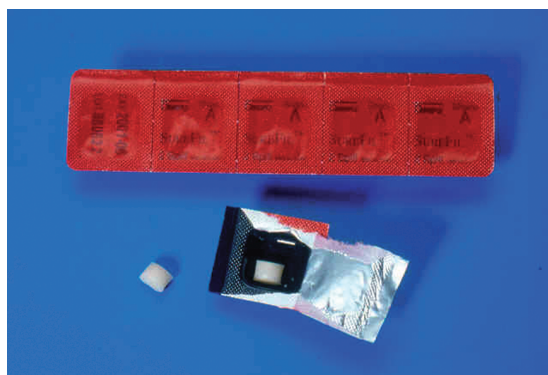
The latter materials are specifically designed for the production of composite inlays and onlays.

- Class 3 materials are dual-cure materials which have a self-curing chemical mechanism but are also cured by the application of external energy.

Another method for classifying composite materials which has been developed and used by the manufacturers recognizes the fact that many dentists choose materials based upon their handling characteristics. Hence, some highly viscous materials are classified as ‘packable’ composites whilst some more fluid products are classified as ‘flowable’ composites. There is an understanding that the choice of packable or flowable material may vary depending upon the particular clinical application. Figure 22.8 shows a packable material which has a viscosity which is so high that it cannot be extruded through a syringe or compule and an alternative means of providing the material in small portions of paste sufficient for one restoration has been devised.

### 22.5 Properties of composites

Some of the properties of resin-based restoratives are included within the tests and requirements of the ISO Standard (ISO 4049). This standard sets



**Fig. 22.8** Some very viscous light-activated materials cannot be extruded from syringes or compules and they may be provided in containers of the sort shown here. The viscous material does not require any mixing and can be packed directly into a prepared cavity. Materials of this sort are sometimes referred to as packable composites.

minimum standards of quality in relation to the following:

- (1) The working time and setting time of class 1 materials.
- (2) The sensitivity to ambient light and depth of cure of class 2 materials.
- (3) The flexural strength of type 1 and 2 materials.
- (4) The water absorption, solubility, shade, colour stability and radiopacity of all materials.

*Biocompatibility:* Whilst composites are considered to be generally acceptable in terms of biocompatibility they should be treated as potentially harmful materials and handled with caution. The potential risks with composites are discussed in comparison with mercury in dental amalgam in Section 21.4. As with most materials, the products are potentially more harmful before setting when smaller molecules are not strongly bound within the mass of material. After setting the rigid cross-linked structure helps to bind potentially harmful components more tightly.

*Setting characteristics:* For chemically activated materials, setting commences immediately after mixing the two components (paste and paste or paste and liquid etc.). The rate of set is uniform throughout the bulk of the material causing a gradual increase in viscosity at room temperature. Hence, the materials have a limited working time and must be inserted into the prepared cavity before they become unmanageable. In ISO 4049 the working time is determined using a thermocouple located at the base of a small cavity (6 mm deep by 4 mm diameter). The working time is taken as the time when the exothermic heat of reaction for the mixed material causes a noticeable rise in temperature. The standard requires that the working time (timed from start of mixing) should be at least 90 seconds.

After insertion, the materials are held under pressure with a plastic matrix strip and setting is normally completed within two or three minutes. Since setting occurs uniformly throughout the material it is safe to assume that a hard surface indicates that the material has set right through to the base of the cavity. Any material which is not covered by the matrix during setting is likely to have a tacky surface layer due to inhibition of the polymerisation reaction by oxygen. In ISO 4049



the setting time is determined using the same apparatus as that described for measuring working time. For setting time determinations the equipment is maintained at mouth temperature (37°C). The setting time is defined as the time to reach the peak temperature in the exothermic setting reaction. The setting time measured by this method must be no more than 5 minutes.

For light-activated materials, only a minimal increase in viscosity takes place before the material is exposed to the activating light source. With these products the operator has, therefore, a longer working time. It should be remembered, however, that visible light-activated materials do begin to set slowly after exposure to light, particularly light of high intensity such as the surgery operating light. Therefore, insertion of the material into the cavity should not be delayed longer than necessary. In ISO 4049 light-activated materials are required to be tested for sensitivity to ambient light. When subjected to lighting equivalent to a dental operating light they should show no detectable change in consistency after 60 seconds exposure. After being covered with a matrix strip and exposed to the light source, polymerisation is often very rapid. Exposure times of between 10 seconds and one minute are, typically, required to cause setting. This ability to set rapidly after exposure to a light source is termed *command setting*.

The pattern of setting for light-activated materials is dictated by the fact that activation is first achieved in the surface layers of material where the light intensity is greatest. The potential for activation declines exponentially as a function of the distance from the surface of the filling. The intensity of light  $I_x$  at a distance  $x$  from the surface is given by the function

$$I_x = I_0 e^{-\mu x}$$

where  $I_0$  is the light intensity at the surface and  $\mu$  is the absorption coefficient of the material. Since a certain level of intensity is required to cause activation it follows that light-activated materials have a *limited depth of cure*. The high viscosity of the pastes retards the diffusion of active free radicals from the surface layers to the lower unactivated layers, hence, material which is not activated initially may take a considerable time to set or may remain unset indefinitely. In ISO 4049 depth of cure is evaluated simply using a *scrape* test. Material is packed into a cylindrical mould and

cured from one end for the time specified by the manufacturer. Immediately after curing, the mould is opened and any soft uncured material is removed using a plastic spatula. The height of the remaining hard, cured material is used to indicate depth of cure. In recognition of the fact that the method is quite crude and that material near the centre of the mass of material cures to a greater depth than the edges, the measured value is divided by 2 to give the final calculated depth of cure. This should be no less than 2 mm for most materials. A lower value of 1 mm is allowed for opaqueing materials.

Manufacturers of light-activated composites can control depth of cure by formulating the products in such a way that they more readily allow light penetration. In addition, they can supply or recommend a light source of adequate intensity and stipulate the exposure time required to give a certain depth of cure. Darker and more opaque shades of materials cannot be cured to the same depth as light and translucent shades. As an example, the light paste of one material can be cured to a depth of 2.5 mm using a 30 second exposure to light. The brown, opaque paste of the same material can only be cured to a depth of 1 mm using the same exposure time. Increasing the exposure time has very little effect on the depth of cure. If a material cures to a depth of 2.5 mm following a 30 second exposure it will not be cured to a significantly greater depth by increasing the exposure time to 1 or 2 minutes. On the other hand, the depth of cure can be significantly reduced by using a light exposure time of less than that recommended by the manufacturer.

The compatibility of light sources and composite materials has been the subject of several studies and debates. Most currently available light-activated composite materials utilize a similar catalyst system and most light-activation units are designed to deliver radiation which has a high intensity at the relevant wavelength. There are marked differences in performance between the units however, with a variation in intensity of light at 470 nm of up to ten times (130–1300 lux at 470 nm). Since depth of cure values which are supplied by manufacturers have normally been measured with a specific light source, it cannot be guaranteed that the same depth of cure could be achieved with a different light source.

Other factors can be controlled by the operator. The distance of the light source from the surface

of the material is important. Depth of cure decreases significantly as this distance increases. The operator should never attempt to cure a greater depth of material than that recommended by the manufacturer, nor should he attempt to use a shorter exposure time. When large cavities are being restored the composite material should be cured in increments to ensure proper curing.

The polymerisation reaction which causes setting of composite materials is exothermic in nature. The heat liberated can cause a significant temperature rise within the material. If the temperature rise is excessive and the pulp is not effectively insulated, irritation, sensitivity or more serious irreversible damage may be caused. The heat of reaction for chemically activated and light-activated materials is of similar magnitude but the resulting temperature rise varies considerably. In the case of a typical chemically activated material the temperature rise is expected to be in the range 1–5°C for an average size of restoration. For light-activated materials the temperature rise is typically 5–15°C depending upon the monomer system used and the filler content. The temperature rise is much higher for light-activated materials because the heat of polymerisation is liberated over a much shorter time-scale. In addition, the heating effect of the light-activation unit further increases the temperature of the composite material when it is illuminated. In order to minimize the latter effect, manufacturers incorporate filters into their light-activation units. These filters are designed to remove the ‘hotter’ parts of the white light which occur at the red end of the visible spectrum. Hence, the radiation used in most units appears blue.

*Light activation units:* The purpose of the light activation unit is to deliver high intensity radiation of the correct wavelength to the surface of the material in order to activate polymerisation. The critical wavelength used by the vast majority of units and materials is 470 nm which corresponds to the blue region of the visible spectrum.

Several types and designs of light activation unit are available for activating the polymerisation of light-activated materials. The conventional type of blue visible light activation unit used in dentistry since the early 1970s (shown in Fig. 22.5) is based upon light produced by a quartz tungsten halogen bulb (often shortened to QTH or halogen bulb)

equivalent to that used in motor car headlights or slide projectors.

The design of the light curing unit is either a light box with a flexible fibre-optic umbilical and a light wand that is used to illuminate the restoration or a gun design where the bulb and cooling fan are located in a hand-held device with a rigid fibre optic light guide protruding out of the front of the gun to conduct light to the restoration. There are problems with all fibre-optic systems in that the glass fibres break with time reducing the efficiency of light transmission. This is a greater problem with flexible bundles than with rigid light guides. Both designs will include a cooling mechanism for the bulb, a timing unit and filters to remove some of the unwanted spectra produced by incandescent light sources, particularly the ultra-violet end of the spectrum.

Halogen lamps are the most widely used and are available in both designs. They are capable of generating the required power of light output and are relatively cheap. The power output from the bulb deteriorates as the bulb ages reducing the effectiveness of the curing process. These bulbs produce a broad spectrum of light and require appropriate filtration to eliminate harmful elements of the light spectrum. They also generate a considerable amount of heat both directly and through emissions in the infra red range of the light spectrum.

*Alternative light delivery systems:* The light energy can now be delivered through other alternative means using plasma arc, laser or light emitting diode (LED) systems (Fig. 22.5). These delivery systems vary in the spectral distribution of radiation produced and in the power or intensity of radiation over the critical wavelength region. In the case of camphoroquinone the optimal absorption of radiation occurs at 460–480 nm and systems which produce high intensity radiation outside the effective region are likely to be inefficient. They may require filters to remove unwanted radiation and cooling systems to reduce the effects of some of the radiation which causes heating but is ineffective in activating polymerisation. Such is the case with QTH type lamps described above.

The plasma arc lamps use a Xenon bulb which works on the same principle as a motor vehicle spark plug. A spark is produced by generating a large potential difference across a gas which becomes ionized to form the ‘plasma’. Plasma arc

lights are more commonly available in the light box/umbilical/light wand design. The power output from the bulbs is considerable (most are of the order of 300 watts) and require very efficient cooling systems. There are a smaller number of recently designed products that use a new design of light and reflector working at 120 watts that can be mounted in a gun design. The power output from these light units is about ten-fold that of a halogen bulb resulting in considerably shorter curing times and possibly greater depth of cure. There is also a significant heating effect with these bulbs through the infrared spectrum.

The total amount of light generated for plasma lamps is significantly greater than in the QTH lamps. Filtering is required to remove radiation with <400 nm or >500 nm wavelength and exposure times much shorter than those with QTH lamps are recommended. Typically, only 2 or 3 seconds of exposure is required with plasma arc lamps to achieve the same depth of cure obtained with a 30-second exposure to a typical QTH lamp. The timer on the control unit for these plasma arc lamps normally allows exposure times of only a few seconds followed by a latent period during which further exposure is not allowed. This prevents undue tissue heating which may result from over-exposure. Nevertheless, high temperature development is still a source of some concern with these systems.

Argon lasers emit a blue light which can be used to activate polymerisation. Two potential advantages of laser light are: (1) the radiation is produced in a narrow wavelength distribution which, if matched to the absorption spectrum of the initiator/activator system, results in increased efficiency (2) lasers are capable of emitting a collimated beam of radiation which may travel a large distance without dispersing. This characteristic is in contrast to the normal behaviour of light in which the natural dispersion of radiation results in a rapid decrease in intensity as the distance from the source increases. In practice, laser curing units often employ a diffuser which disperses the radiation into a cone to produce improved coverage of a larger area. Laser curing units can achieve a degree of polymerisation and a depth of cure similar to that achieved with other systems, in a time which is shorter than that required for QTH units but longer than that required for plasma arc units. The efficiency of the light production ensures that heat production is minimized. The narrow

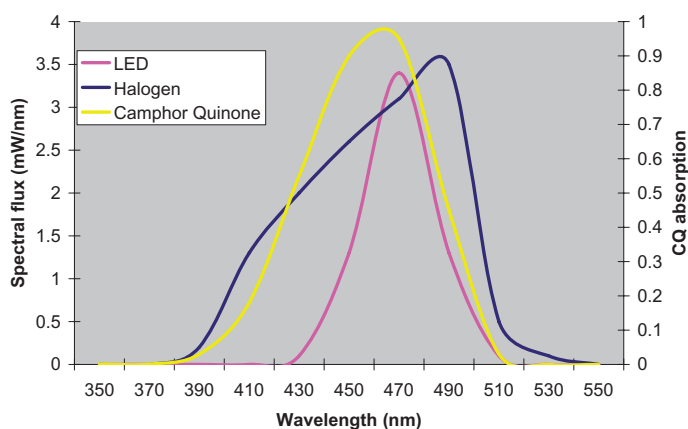
wavelength distribution of the laser systems means that the radiation may be incompatible with a small number of resins which employ different photoinitiator systems. Also, the nature of laser light dictates that these systems are subjected to greater national and international regulation relating to safety, warnings and the appropriate training of personnel.

Light emitting diodes (LEDs) have become used in many areas of technology and certain LEDs emit blue light over a narrow wavelength band which closely matches the absorption spectrum of the most commonly used photoinitiators (see Fig. 22.9). Light emitting diodes are completely different in their technology. An LED is a semiconductor that emits light within a very narrow frequency band when an electric current passes through it. A *standard* diode does not fluoresce in function but when the diode is *doped* with specific metals at low concentration fluorescence occurs. For example an aluminum gallium phosphate doped LED emits green light; light in the blue frequency bands is developed from diodes doped with gallium nitride, indium gallium nitride, silicon carbide, sapphire (aluminium oxide) and zinc selenide.

LEDs have a number of advantages over incandescent bulbs:

- Their low current use enables the practical design and manufacture of portable, rechargeable light curing units which are environmentally sealed facilitating cross infection control.
- They emit virtually no heat during use which will reduce the thermal change that a tooth is subject to during curing to only that of polymerisation reaction.
- They have a limited and specific spectrum of light output that can be tailored to a specific activity like activation of a photo-sensitive initiator for resin curing.

Curing units based on blue light LEDs have the advantage of low power consumption with battery power becoming a feasible option. There is no need for a filtration system and minimal heat is produced. The LEDs generally have a long service life with no bulbs to change, have a consistent output and are quiet because there is no need for a cooling fan. As for laser systems, a few products employing less common photoinitiators may be incompatible with the specific wavelength band of the LED light.



**Fig. 22.9** The spectral distribution of light output from LED curing lights corresponds to the absorption spectrum for the commonly used photo-initiators for light-cured composite resins. Conventional halogen light sources have a much wider light spectrum including elements from the infrared range which contribute to heat generation during the curing of composite resins. Adapted from Neumann M.G. *et al. Dental Materials* 2006:22,657–684.

**Compatibility and testing:** The compatibility of composite material and light curing unit remains an issue of concern on which much research is focused. Regular testing of equipment and materials is recommended to ensure adequate curing of materials. All of these light sources will fail with time. The pattern of failure for all can either be catastrophic or there will be a gradual deterioration of light output with ageing of the bulb/LED. The life expectancy of LEDs is considerably longer than incandescent bulbs. For this reason it is important clinically to monitor the optical power output of light curing units and to change the bulb if the lower output falls significantly.

An ISO standard for dental curing light units has been in preparation for several years. Difficulties in preparing an acceptable standard arise from the fact that it is difficult to divorce the performance of the lamp from that of the material. Nevertheless, manufacturers have produced a number of devices which can be used to monitor the quality of light-curing units. Many consist of light-sensitive diodes which are used as light-intensity meters. When the reading falls below a critical value it suggests that the unit needs attention – perhaps a bulb needs replacing. Another approach to quality control is to carry out a depth of cure test using the chosen light unit/composite combination. Such testing performed on a regular basis is probably the best way to monitor the performance of both curing unit and material. At least one manufacturer supplies an easily assembled three-part mould to enable this determination to be made (see Fig. 22.10).



**Fig. 22.10** A 3-part mould of this sort can be used by the dentist to make an estimate of depth of cure. The mould is assembled and composite material is packed into the cavity and cured by exposure to a curing lamp. The mould is then disassembled and a probe can be used to estimate the depth at which material remains soft. Regular determinations can be used to confirm that both material and curing equipment are in good order.

**Setting contraction:** The setting contraction of composite resins is considerably smaller than that observed for unfilled acrylic resins. Two factors contribute to this reduction. Firstly, the use of larger monomer and comonomer molecules effectively reduces the concentration of reactive groups in a given volume of material. Secondly, additions of fillers which take no part in the setting reaction further reduce the concentration of reactive methacrylate groups.

The setting contraction depends on the number of addition reactions which take place during polymerisation and is therefore much smaller for

composite materials. Values of around 1.5–3.0% volumetric contraction are typical as opposed to 6% for acrylics. The setting contraction varies from one type of composite to another. Products with higher filler loadings undergo less shrinkage since there are fewer reactive groups participating in the setting reaction. Heavily filled hybrid materials exhibit the lowest shrinkage values. Micro-filled materials generally have lower shrinkage values than would be expected from their low filler contents. It should be remembered however that these materials contain prepolymerised resin filler in addition to the inorganic filler material. The total volumetric proportion of combined inorganic and resin filler is often equal to, or greater than, that present in conventional or hybrid products and gives a value of shrinkage which can compare favourably with that for other materials. The type of resin used may influence shrinkage. Bis GMA has a relatively low setting contraction but this is increased proportionately according to the amount of diluent monomer (e.g. TEGMA) used. High molecular weight urethanedimethacrylate monomers which are often fluid enough to be used without diluents may give a lower value of contraction.

Very recently, manufacturers have been able to develop resins based upon oxirane, silorane or similar derivatives which undergo addition polymerisation through ring-opening of an oxirane ring. This process creates a slight volume expansion which reduces or eliminates the setting contraction.

Shrinkage can compromise marginal seal (Fig. 22.11) and rupture adhesive bonds created at the tooth-restorative interface. The total amount of volumetric contraction which occurs depends upon the bulk of material used and hence on cavity size and clinical technique. Some materials are expected to perform quite well in small cavities where the contraction may be small enough to ensure that marginal adaptation is maintained. The same product may undergo sufficient contraction to cause breakdown of marginal seal in larger cavities. Layering techniques, particularly applicable to use with light-activated materials, can be used to limit the damaging effects of shrinkage. In addition, it has been claimed that the slight expansion, due to absorption of water, which gradually occurs in some materials over a period of several weeks following placement can help to partially off-set the effects of shrinkage.

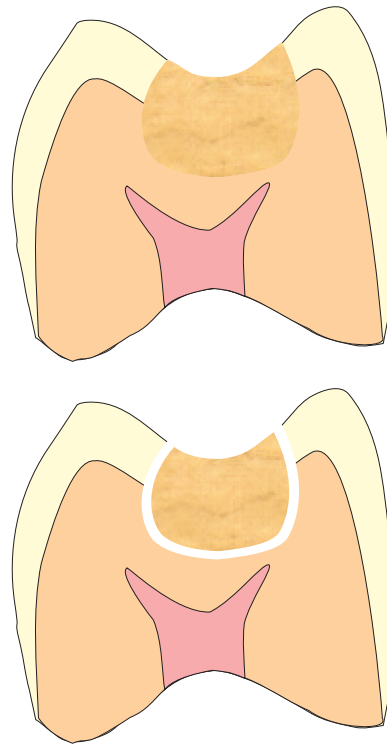


Fig. 22.11 Shrinkage of a filling material during polymerisation can potentially cause the formation of a marginal gap. This may seriously compromise the long term viability of the restored tooth. Top – freshly placed restoration before polymerisation. Bottom – after polymerisation, illustrating the formation of a gap.

Another potentially serious effect of shrinkage is thought to be the stress placed on tooth substance, particularly on the residual cusps of posterior teeth when composite materials are used in relatively large class II cavities. Such stresses, caused by the composite material ‘pulling-in’ cusps to which it may adhere, is thought to be responsible for some cases of post-operative pain experienced after placement of so-called posterior composites. In extreme cases the stress on the tooth may be great enough to cause cuspal fracture.

For light-activated materials, different modes of curing have been advocated in order to achieve optimal conversion of monomer to polymer whilst minimizing the effects of polymerisation shrinkage. Most notable amongst these approaches is the ‘soft-start’ curing in which the light activated material is subjected to a short exposure or low



power exposure of activating radiation followed by a short delay and then a longer or higher power exposure to complete curing. The aim is to enable the early polymerisation phase to occur slowly enough to enable the shrinkage stress to be dissipated through the flow of the relatively soft material. This method also has the potential to reduce the temperature rise resulting from polymerisation as the reaction time is lengthened. There is little evidence to show whether or not this approach is effective.

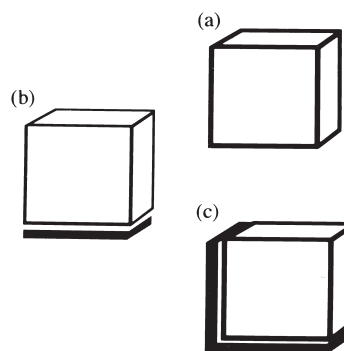
The direct measurement of the volumetric shrinkage of composites during setting has proved difficult – a fact which probably explains the lack of a test for this property in the ISO Standard. Simple dilatometric methods are difficult for various reasons including the high initial viscosity of the composite pastes and the setting characteristics which allow inadequate working time to set up a dilatometer (for chemically-activated products) or require access for a light-activation unit (for light-activated products). The method which has emerged as being most practical has been to sandwich the composite paste between two glass plates and to measure the reduction in the plate separation distance as the material sets. Since the vector of shrinkage is normal to the interface between composite paste and glass plates, virtually all the shrinkage is constrained in one direction and the linear shrinkage across the plates reflects the volumetric shrinkage of the composite.

Measurements of shrinkage made using this or similar methods have led to other important observations. First, if the material is allowed to set between two plates which are constrained the contraction stress can be calculated. This gives an indication of the stress which would be set up at a cavity margin or wall and may be a significant factor in determining whether an adhesive bond is disrupted or whether cusp deflection occurs, etc. Measurements of shrinkage stress indicate that the initial shrinkage which takes place whilst the material is still fluid may be of little clinical significance as it can be compensated by the flow of the material. It is the 'post-gelation' rigid contraction which is significant and when we measure shrinkage it is important to identify this component of the overall shrinkage.

The distinction between volumetric shrinkage and the resulting stress is emphasized in publications in which setting of resin matrix materials is

monitored through changes in the shrinkage strain (volumetric shrinkage) or shrinkage stress. Both approaches can yield important information on the rate of set, but the stress determination may be more pertinent to the clinical consequences of the material setting within the confined spaces of a cavity.

The ability of a resin-based filling material to compensate for shrinkage by flow depends on the cavity configuration. When there is a small ratio of contact surface area to free surface area flow occurs readily over the free area in order to minimize the stress at the interface. When there is little free surface area of material, little flow can occur and a larger stress at the interface results. The ratio of bonded:free area can therefore be used to predict interfacial stress caused by shrinkage. The ratio has become known as the C-factor or configuration factor. Further insight into the C-factor can be obtained by reference to Fig. 22.12. If a cube of composite material is completely unconstrained (as in (a)) it can flow readily in all directions in order to minimize the shrinkage stress. The C-factor for this situation is zero. In example (b) the material is bound to a surface across one of the six faces of the cube. There are five free faces over which flow can readily occur (a C-factor of 0.2) and the stress at the interface with the bonded surface will be relatively small. In example (c) the cube of material is constrained at two of the six faces giving a C-factor of 0.5. This will result in a greater stress at the interface as flow can only occur over 67% of the area of the cube. When the material is constrained over



**Fig. 22.12** Diagrammatic illustration of the configuration C-factor. A cube of resin having six faces, is completely free in (a), bound at one face (b) or bound at two of its faces (c). The C-factors for these situations are 0, 0.2 and 0.5, respectively.



five of the six surfaces of the cube (giving a C-factor of 5) flow can only occur at the one free surface and the stress at the five remaining surfaces is much greater. Hence, the C-factor gives an indication of the potential for stress to develop. It is possible to make approximate calculations of the C-factor values which would apply for different cavity configurations, i.e. a class IV cavity approximates to Fig. 22.12c and therefore has a C-factor of 0.5 whereas a class I cavity approximates to a cube constrained on five out of six sides and thus has a C-factor of about 5. The greatest C-factor values will apply when materials are used in thin, constrained layers, such as occurs when the material is used as a luting agent. In this situation C-factor values of greater than 10 may apply.

*Thermal properties:* The thermal properties of composite materials depend primarily on the inorganic filler content. Table 22.2 gives values of thermal diffusivity and coefficient of thermal expansion for a conventional composite, microfilled composite, unfilled acrylic resin and dentine for comparison. It can be seen that as the filler content increases the coefficient of thermal expansion decreases, although even for conventional composites, with 78% filler, there is still a considerable mismatch in values compared to dentine. This mismatch may cause percolation of fluids down the margins when patients take hot or cold foods. The amount of mismatch which can be tolerated without causing clinically significant problems is not precisely known. It is significant, however, that the microfilled composites have values some six or seven times greater than tooth substance.

The thermal diffusivity also depends on filler content although the values for all the materials are close to that measured for dentine and they can all be considered adequate thermal insulators.

*Mechanical properties:* The mechanical properties of composite materials depend upon the *filler content*, the *type of filler*, the efficiency of the filler–resin *coupling* process and the degree of *porosity* in the set material.

Light-activated composites, supplied as single pastes, contain very little porosity whereas chemically-activated composites requiring the mixing of two components contain, typically, 2–5% porosity. The porosity is introduced during mixing. A correctly cured, light-activated, conventional composite may, typically, have a compressive strength value of 260 MPa, whereas an equivalent chemically activated material, containing 3% porosity, is likely to have a compressive strength of 210 MPa. Porosity also has a significant effect on the fatigue limits of composite materials. Non-porous products have a higher fatigue limit and longer fatigue life than porous ones. This may have some bearing on the durability of materials in certain applications.

The lack of an adequate coupling agent pre-treatment of the filler has a dramatic effect on properties. Both the compressive strength and fatigue limit are reduced by about 30% when the coupling agent is not used.

Heavily filled, conventional composites undergo brittle fracture. As the filler content is reduced a transition to a more ductile failure is observed. Microfilled composites, which generally have a filler content of 50% by weight or less, normally exhibit a yield point at a stress considerably lower than that for fracture. Values of compressive strength for microfilled materials are often similar to or even higher than those for conventional composites, but the lower yield stress value is probably more significant for these products since it represents the point of irretrievable breakdown of the material.

The hybrid composites have mechanical properties very similar to those of conventional

**Table 22.2** Thermal properties of typical composite resins.

	Filler content (% by weight)	Thermal diffusivity $\times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$	Coefficient of thermal expansion $\times 10^{-6} \text{ }^\circ\text{C}^{-1}$
Hybrid composite	78	5.0	32
Microfilled composite*	50	2.5	60
Unfilled acrylic	0	1.0	90
Dentine	–	2.0	9

\* Includes nanocomposites.

**Table 22.3** Mechanical properties of composite resins.\*

	Typical microfilled composite	Typical hybrid composite
Compressive strength (MPa)	260	300
Yield stress (MPa)	160	300
Tensile strength (MPa)	40	50
Flexural strength (MPa)	80	150
Modulus of elasticity (GPa)	6	14
Hardness (VHN)	30	90

\* Modern 'nanocomposites' have properties similar to those of microfilled and hybrid products.

**Table 22.4** Flexural strength of resin-based restorations as required by ISO 4049.

Type	Class	Minimum value of flexural strength (MPa)
1	1	80
1	2 (group 1)	80
1	2 (group 2)	100
1	3	80
2	1	50
2	2 (group 1)	50
2	3	50

The different types and classes are defined at the end of Section 22.4.

materials. Strength and modulus values are often slightly higher but not significantly so. Table 22.3 gives values of certain mechanical properties for typical products from each of the three groups of composite materials. The values of compressive strength are for a porosity-free material.

In the past a lot of emphasis has been placed on the compressive strengths of dental restorative materials. Nowadays more emphasis is placed on tensile and flexural strength as it is recognized that these modes of fracture may be more clinically relevant. Table 22.3 shows that the flexural strength and tensile strength of hybrid composites tend to be greater than for the microfilled products. Table 22.4 gives the values of flexural strength required by the ISO Standard (ISO 4049) for different types of material. Type 1 materials (for use on occlusal surfaces) are required to be stronger than type 2 materials (more limited use). Type 1 class 2 (group 2) products which are subjected to extra-oral curing are required to have even higher strength. These products are used to produce composite inlays and onlays. Most

commercially available materials have values of strength well above the minimum values allowed by the standard.

The significantly lower value of modulus of elasticity for the microfilled materials may have clinical significance. These products may potentially deform under stress, leading to a breakdown of the marginal seal. This is recognized as a problem with unfilled acrylics, where a modulus value of 2 GPa is normal. Whether or not the increase from 2 GPa to 6 GPa is sufficient to prevent breakdown is not known.

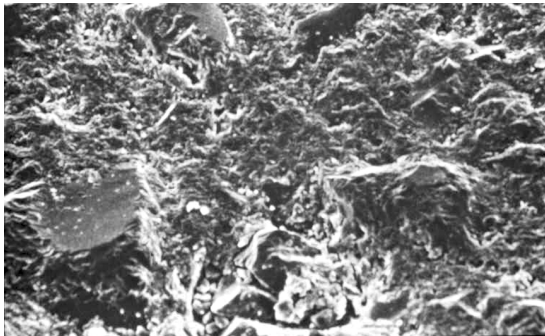
Fracture toughness testing is being used increasingly to give an indication of mechanical strength (see Section 2.2). Tests are carried out on notched specimens and the results indicate the *critical stress intensity factor*. This factor gives an indication of elastic stress distribution near a crack tip when a force is applied of sufficient magnitude to cause fracture. It provides a means of comparing the ability of different materials to resist crack propagation. The value of fracture toughness for a typical conventional composite material is around  $1.2 \text{ MNm}^{-1.5}$ , whilst that for an unfilled acrylic resin is around  $1.0 \text{ MNm}^{-1.5}$ . Some heavily filled hybrid composites have values approaching  $2.0 \text{ MNm}^{-1.5}$ . These can all be considered to be relatively low values when compared with that for mild steel of  $100 \text{ MNm}^{-1.5}$ .

*Surface characteristics:* Surface hardness, roughness and abrasion resistance are properties which are mainly controlled by the filler content and particle size.

The resin and filler have characteristic hardness values which remain independent of filler content. The bulk hardness value of the composite, however, increases as the filler content increases. The Vickers hardness number for

unfilled resin is about 18 whereas that for a heavily filled hybrid composite approaches 100. The microfilled materials have values around 30–40.

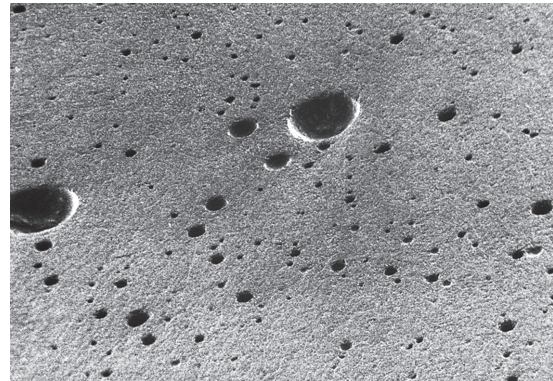
The surface of a composite material is initially very smooth and glossy due to contact with a matrix strip during setting. The surface layer is initially richer in resin than the bulk of the material and few, if any, filler particles are exposed at the surface. Any process of abrasion, however, has a tendency to cause surface roughening as the relatively soft resin matrix is worn preferentially leaving the filler particles protruding from the surface. This is a particular problem with the conventional and hybrid materials which contain relatively large particles (Fig. 22.13). One advantage of the microfill materials is that they retain a relatively smooth surface following abrasion, due to the fact that the hard inorganic particles are very small. Another factor which contributes towards surface roughness is the exposure of porosity voids at the surface by abrasion. This is observed for all types of chemically activated composites, and is illustrated in Fig. 22.14 for a microfilled material.



**Fig. 22.13** Scanning electron microscope photograph of the roughened surface of a conventional composite material showing protruding filler particles ( $\times 750$ ).

Surface roughness may be caused by abrasive forces exerted on materials during service, for example, from foodstuffs, dentifrices etc. Alternatively, roughening may occur during contouring and polishing. The surface cured against the matrix strip should be left intact if possible, but removal of excess material followed by polishing is often necessary. Table 22.5 gives roughness average and gloss values for a typical small-particle hybrid composite following roughening and polishing. The results for the roughened surface refer to a surface abraded intra-orally or ground by the dentist during contouring. The results for the abrasive disc indicate the final result after using medium, fine and finally ‘superfine’ abrasives as the intra-oral polishing procedure.

It can be seen that all of the polishing procedures produce a significant increase in roughness compared to the matrix surface. This is accompanied by a loss of gloss. The polishing method which appears most damaging is the use of rubber points which are impregnated with abrasive.



**Fig. 22.14** Scanning electron microscope photograph of the abraded surface of a microfilled composite material showing exposed porosity ( $\times 325$ ).

**Table 22.5** Roughness average (Ra  $\mu\text{M}$ ) and gloss values (GU) after roughening and polishing. Values are for a typical hybrid type composite.

Surface treatment	Roughness average Ra $\mu\text{m}$ over 80 $\mu\text{m}$ scan length	Gloss units (GU)
Baseline – as set against Melinex matrix	0.08	89
Roughened with sandpaper	0.48	2.7
Polished with medium + fine + superfine discs	0.12	66
Polished with rubber ‘point’	0.32	9.3
Polished with fine polishing paste	0.27	23

The differences in surface roughness given in Table 22.5 appear to be quite small and in most cases  $R_a$  remains less than  $0.5\ \mu\text{m}$ . However, small differences in roughness can have a large effect on gloss. Surface gloss is the property which is responsible for a lustrous surface. Gloss is a measure of the amount of light reflected from a surface at a predetermined angle ( $60^\circ$  is common) compared with the light reflected from a standard black glass surface. A change in roughness from  $0.1\ \mu\text{m}$  to  $0.5\ \mu\text{m}$  can cause the gloss to decrease from 90 gloss units to 2 gloss units. This effectively represents a change from glossy to matt.

A smooth surface can be restored to a roughened composite by using a *glazing agent*. These consist of resins which are identical to composites except that they do not contain filler particles. The glaze is applied to the surface of the composite and sets to form a smooth surface layer of about  $100\ \mu\text{m}$  thickness. The material is very soft, however, and is soon abraded, revealing the composite surface again.

If the rate of material loss due to abrasion becomes excessive it may cause a change in the anatomical form of the restoration. Abrasion of this magnitude may, conceivably, be caused by one of a variety of mechanisms and is of particular importance when considering the use of composites in posterior cavities. Here, the forces exerted on materials are relatively high and abrasive wear may take place at a rapid pace due to either two-body contacts, normally involving the restorative material and an opposing tooth cusp, or three-body contacts in which an abrasive foodstuff maybe involved as the third body between the material and opposing tooth cusp. Cyclic masticatory loadings also offer a potential for fatigue wear in which surface failure occurs following the development of small surface or sub-surface cracks over a period of time. The process of wear, whether occurring by a fatigue or abrasive mechanism, may be accelerated by chemical factors. Certain solvents occurring naturally in some drinks and foodstuffs may soften the resin component of the composite. Other chemical agents, particularly acids, may cause degradation of the filler component and this process is probably accompanied by, or preceded by, the breakdown of the filler–matrix bond. Indeed, following storage of some composite materials in erosive media it is often possible to detect metallic ions from the composite filler in the storage liquid.

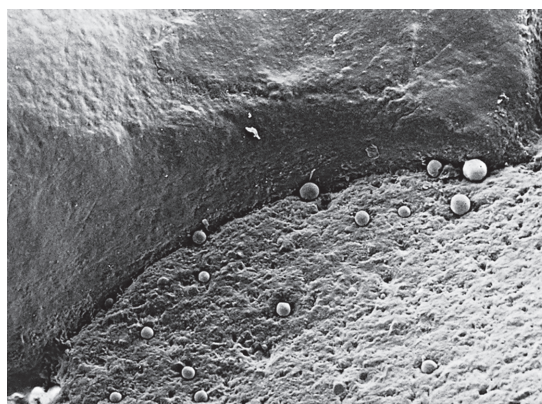


Fig. 22.15 Scanning electron microscope photograph of the margin of a composite restoration showing loss of material due to wear ( $\times 83$ ).

These chemical processes may significantly affect the perceived rate of wear.

Wear resistance of composites designed for use in posterior cavities has improved markedly over the past few years. Most modern products wear at a rate of  $10\text{--}30\ \mu\text{m}$  per annum. Some products undergo a generalized loss of material including that at the cavity margins (Fig. 22.15). This type of wear is relatively easy to detect and monitor using a sharp probe either directly in the mouth or on a cast. Wear which takes place primarily in the occlusal contact areas is more difficult to evaluate and is likely to be more rapid.

**Appearance:** Composite materials, when freshly placed, offer an excellent match with surrounding tooth substance. The availability of a variety of shades, combined with a degree of translucency imparted by the filler, enables the dentist to achieve a very pleasing result. Polishing reduces the gloss, however, and abrasion may further increase surface roughness. The surface may eventually become stained due to deposition of coloured foodstuffs or tobacco tars. The microfilled products are capable of maintaining a smoother surface than either the conventional or hybrid materials. Providing the resin of the material is inherently colour stable or contains effective stabilizers these products should be more resistant to surface staining.

**Cavity linings:** Although monomers employed in composite materials may be considered potentially harmful to the pulp, they are generally strongly



bound in a highly cross-linked network following setting. There is an inevitable tension between the perceived need to protect the pulp from these monomers and the requirement for the composite and its bonding agent to be in intimate contact with the dentine for bonding to occur. Providing there is not an overt pulpal exposure, linings are no longer used. When an exposure or a 'near miss' happens then it may be prudent to use a small lining of a fast setting calcium hydroxide material over the pulp itself.

**Adhesion:** Composites do not inherently form a durable bond with tooth substance. Retention of the material is generally achieved by using undercut cavities. This often involves removing significant quantities of sound tooth substance.

Methods of establishing a bond between composites and enamel or dentine are discussed in Chapter 23. Such techniques greatly increase the number of potential applications of the materials and also offer a means of preventing microleakage.

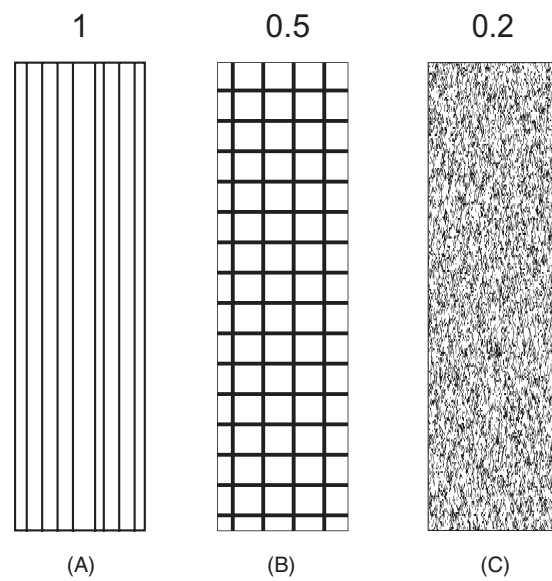
## 22.6 Fibre reinforcement of composite structures

The use of glass or carbon fibres to reinforce composite resins has recently been developed in two areas; for posts used when managing root filled teeth and to provide composite structures of sufficient toughness to make bridges.

The reinforcement that is imparted to a composite material by the incorporation of fibres depends on the quantity of fibres, their orientation, the quality of bond between the fibres and the resin and finally the fibre length. Fibre length is only relevant when fibres are short as there is a critical length for each type/size of fibre below which it acts more as a conventional filler particle rather than imparting additional toughness to the material. Once fibres exceed this critical length the reinforcement depends on the fibre loading and orientation.

The stages in construction of a fibre reinforced composite bridge are illustrated in Fig. 22.17a–d.

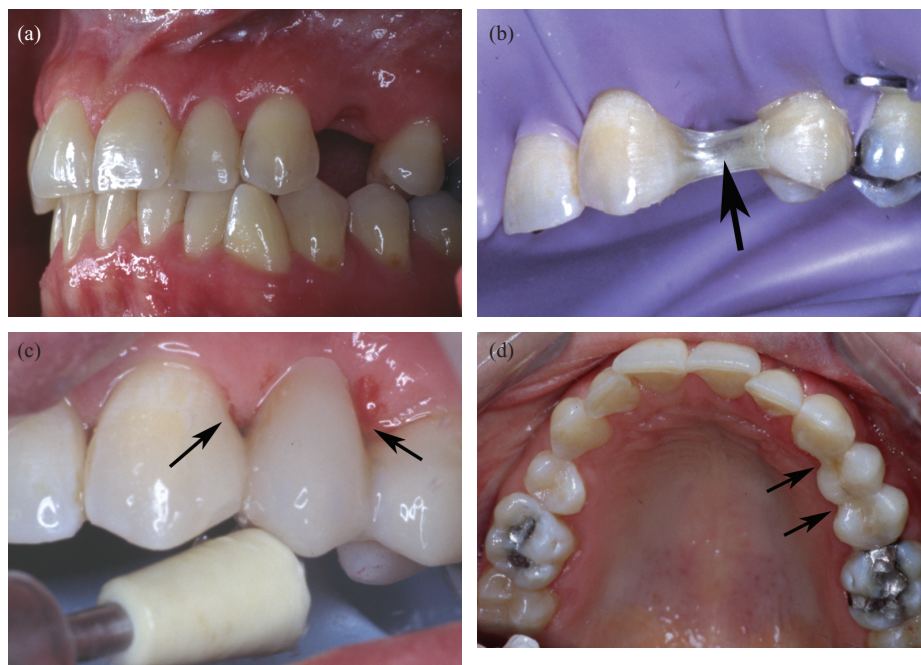
The efficiency of reinforcement for any given level of fibre loading is described by the *Krenchel factor*. A material has a Krenchel factor of 1 when the fibres are oriented in one direction (Fig. 22.16); this gives the maximum level of reinforcement for



**Fig. 22.16** Various patterns of fibre loading give different levels of reinforcement and physical properties of the material. A uniaxial fibre orientation resulting in an anisotropic material with a Krenchel factor of 1 (A), biaxial fibre mat resulting in an orthotropic material with a Krenchel factor of 0.5 (B), random fibres orientation resulting in an isotropic material with a Krenchel factor of 0.2 (C) providing the fibres are longer than the critical length for that fibre type.

a given fibre loading but produces a material which is anisotropic (i.e. it has markedly differing properties when tested in different orientation). When fibres are arranged perpendicular to each other the efficiency of reinforcement is reduced by 50% in any one direction (Krenchel factor 0.5) and the resultant material is likely to be orthotropic (i.e. it will have similar properties in two planes of testing that relate to the orientation of the fibres but markedly differing properties if tested in other planes). Finally a random orientation of fibres results in a material which is isotropic (having similar properties in all directions) but in which the efficiency of reinforcement is only 20% (Krenchel factor 0.2) in all directions. The efficiency of reinforcement will also be influenced by the orientation of the fibres in relation to the strain they are designed to resist (Fig 22.17a–d).

The ability of the fibre reinforcement to combine with the resin composite is also vital in their effectiveness. Most fibres that are used clinically



**Fig. 22.17** Illustration of the technique for making a fibre reinforced composite resin bridge *in situ* (With permission from Pekka Vallittu and Katja Narva, Turku, Finland.)

(a) The edentulous span prior to bridge placement for 24

(b) The fibre sub-structure in place, these are uni-axial fibre mats with fibre orientation along the mat (across the span), there are 2 crossed pieces of mat in place, the first runs from the palatal of 23 to the buccal of 25 and the second from the buccal of 23 to the buccal of 25

(c) The completed bridge during final polishing from the buccal, note that the embrasure spaces have been maintained to facilitate cleaning (arrows)

(d) The completed bridge from the occlusal, note the wide contact areas between composite and tooth in the proximal contacts to the distal of 23 and the mesial of 25 to maximise support and retention.

are presented as pre-impregnated fibre/resin mats or cords. One manufacturer has also developed a novel semi-interpenetrating polymer network to enhance this effect. This is based on a mixture of PMMA and BisGMA resins.

### Fibre posts

Fibre posts for root filled teeth use either glass or carbon fibres (carbon fibres are black which limits their use in other settings) for reinforcement and the fibres are arranged uniaxially along the long axis of the post. These posts are designed to have similar physical characteristics to dentine and are bonded in place using a composite luting agent and dentine bonding system to maximize the attachment between post and tooth. One significant challenge when using this type of post is an

appropriate technique to achieve a bond between the resin lute and root dentine. A total etch technique (see p. 236) is most commonly used as the setting reaction of the lute is chemically initiated. This requires great care in terms of etching the root dentine, washing the acid out of the root and then controlled drying to maximize the bond strength. Very careful clinical technique is essential and drying must be achieved using a blotting approach, most commonly with paper points. A composite resin core is then built up around the post with the composite also being bonded to the remaining coronal dentine. The vast majority of such posts come as preformed structures of fibre reinforced resin of standard taper and with a limited range of diameters. The root canal is prepared using standard tapered burs which match the sizes of the preformed posts. An alternative



technique is available in which pre-impregnated sticks of fibre are moulded to the shape of the canal under pressure prior to polymerisation of the custom post out of the mouth and subsequently luting the custom post in place in a similar manner to above. Currently there is no clinical evidence to suggest which technique is superior.

There are two significant clinical advantages to the use of fibre posts compared with metallic posts.

- The physical characteristics of the post and tooth are similar, consequently failure of a fibre post is less likely to be associated with catastrophic failure of the tooth root (root fracture); rather the post snaps or it is pulled out of the root.
- When a glass fibre reinforced post is used the aesthetics of the core are maximized which is a potential benefit if the definitive restoration for the tooth is planned to be one of the new translucent all ceramic materials.

#### *Fibre reinforcement for bridges and splints*

Composite resin has inadequate physical properties to allow it to be used for bridgework without some form of reinforcing sub-structure. Resin impregnated mats of fibre can be used for this purpose for short span structures, made either in the laboratory with conventional designs of tooth



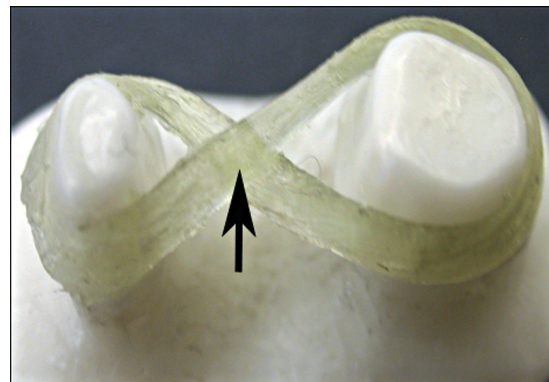
**Fig. 22.18** A fibre reinforced bridge made in a laboratory prior to bonding into the patient. The design is similar to a ceramo-metallic adhesive bridge. Note that the wings are thicker than those where metal is used as the fibres need to be covered in composite for durability. The advantage of this material is that the wings are tooth-coloured so there is no risk of metal 'shine through' causing greying of the abutment teeth. With permission from Pekka Vallittu and Katja Narva, Turku, Finland.

preparation (Fig. 22.18) or directly at the chair-side using an approach similar to conventional adhesive bridgework with the fibre mat being bonded to the supporting teeth on either side of the span and a composite resin pontic built up at the chairside (Fig. 22.19).

These materials exhibit sufficient physical strength to allow for closure of short spans. One challenge is that the fibre mats need to be encased in resin for durability. It is a particular problem if the fibre mat is exposed during finishing and polishing of the restoration. The bond between the fibres and their resin coating is relatively susceptible to breakdown in an aqueous environment and failure by delamination of the fibre reinforcement will rapidly follow.

#### *Fibre reinforcement of direct filling composites*

There have been some attempts to use fibres as part of the filler load within composite resins. The early attempts used very short fibres where the fibre length was below the critical length that would allow the benefits of fibres as a reinforcement. Commercial fibre reinforced materials designed for core build-up are now available which claim a 10% improvement in their physical properties compared with conventional materials. There are also some experimental clinical materials under evaluation.



**Fig. 22.19** Figure of 8 reinforcement using uni-directional fibres for a conventional bridge manufactured from fibre reinforced composite resins. Reprinted from *J. Dent* **35(5)**, Garoushi et al, 403–8, 2006 with permission from Elsevier.

## 22.7 Clinical handling notes for composites

One common failing amongst dentists is their failure to adopt new techniques which are appropriate to new materials. New products are often used in the same way as existing materials without due thought being given to modifying technique and applications to maximize the physical performance of the materials concerned. Whenever dentists are faced with a new material they should ask 'What are the properties of this product?'. 'How can I or should I change what I usually do to maximize the performance of any restoration I produce with this material when compared with the one I have used previously?' These are questions that have been answered historically only after a material has been unsuccessful when used in a 'classical' manner. This can result in a material gaining a bad reputation undeservedly and in a delay in its acceptance by the profession to the detriment of patient care. A case in point are the dental composites. These materials are very different in physical characteristics to their predecessors (either dental silicate cements or amalgam) and yet were used initially in *amalgam cavities* where their performance was less good than it is now that attempts have been made to adopt cavity design and placement techniques better suited to their physical characteristics and handling properties.

### *Cavity design and bonding to enamel*

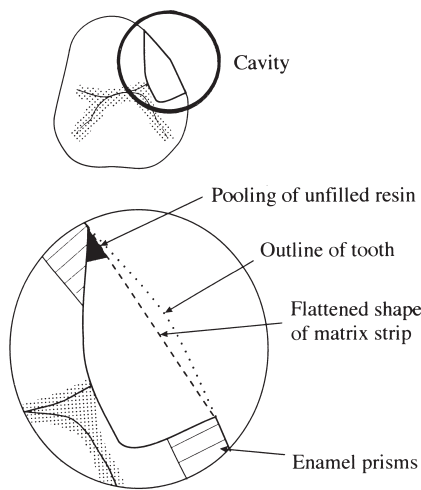
The ability of composites to form a durable seal to both enamel and dentine has allowed modifications to cavity design to both minimize the destruction of otherwise sound enamel and dentine and to maximize the performance of these restorations. Access through enamel should be sufficient to permit removal of underlying decayed dentine.

Composite resins exhibit good flow characteristics in their prepolymerised form. Cavities should be designed to use this property with rounded internal line angles and smooth flowing contours. Smaller cavities produced as a result of caries removal alone will help to reduce the potential for wear of the composite, as a consequence of the remaining tooth structure providing some protection from functional contact. Traditional cavity design has included the removal of deep tortuous fissures adjacent to areas of decay as these were regarded as being at high risk from carious attack.

This is not required when using a composite as these areas can be prepared and then sealed using a compatible fissure sealant system to achieve *extension for prevention*.

Cavities designed for tooth-coloured restorations rely heavily on their bonding to enamel and/or dentine to achieve retention and resistance to displacement. If a restoration is to be placed under high functional load it may be sensible to augment this chemical attachment by the preparation of macro-mechanical undercuts where possible. It is just as important, however, to remove unsupported enamel from cavity margins with composites as it is with amalgam, although for different reasons. The margins of a cavity for a composite restoration are treated to achieve a chemical and/or mechanical link between resin and tooth. Once this link is established then the forces that are generated by polymerisation shrinkage of the composite are transmitted to the tooth through the enamel margins. If the enamel at these margins is unsupported then there is an increased risk that the enamel prism structure will be disrupted by the shrinkage of the resin, resulting in a failure of marginal seal.

Once any unsupported enamel has been removed, the cavity margins need to be designed to maximize the bond strength that can be achieved with either enamel or dentine. Attachment of composites to enamel is achieved primarily by etching the enamel surface with acid as described in the next chapter. This etching process results in preferential dissolution of either the enamel prism cores or the prism boundaries, producing a microporous enamel surface with high surface energy. The pattern and quality of etching depend on the acid used and also on the orientation of the enamel prisms in relation to the cavity margin. Classically, enamel is etched with between 30 and 37% phosphoric acid, although more recently a wider variety of acids have been used including 10% phosphoric, nitric and maleic. The etching time is specific to a given acid and hence manufacturer recommendations should be followed with care. Enamel prisms can be etched in any orientation. However, the quality of the etch pattern is better when they are etched perpendicular to their long axes as opposed to parallel to the prism orientation. Unfortunately the production of a 90° cavo surface angle giving well supported enamel margins will result in prisms being exposed for etching parallel to their long axes. Production of



**Fig. 22.20** If a class II cavity is prepared with an oblique finishing margin there is a risk of unfilled resin pooling in the narrow cleft at the edge of the box. This is a particular problem when clear matrix strips are used as these tend to flatten across the proximal box, making the cleft even narrower.

a cavo surface angle of the order of  $120^\circ$  will help to overcome this problem by exposing a combination etch pattern, although it is not as easy to finish a tooth-coloured restoration accurately to an oblique margin. Additionally, enamel is an anisotropic material with markedly different mechanical proportions when measured at different orientations to the enamel prisms. Enamel is toughest when loaded perpendicular to the tooth surface and weakest when loaded parallel to the surface (this would include loads applied to the enamel prisms on cavity walls).

This approach (the  $120^\circ$  cavo surface angle) is acceptable for cavities where a tightly adapted matrix band is not required during the initial stage of restoring the cavity. This is not the case for class II cavities (those involving two surfaces of molar or premolar teeth) where a matrix in a band holder is used to help form the shape of the tooth surface. In this situation the unfilled resin that is used to initiate the bond between composite and tooth tends to pool in the V-shaped defect formed between the matrix and an obtusely finished cavity margin (Fig. 22.20). This produces a marginal finish formed from unfilled resin which is both weak and prone to wear/degradation in function

in an area where both problems are to be avoided if possible. In this circumstance a  $90^\circ$  cavo surface angle is preferable.

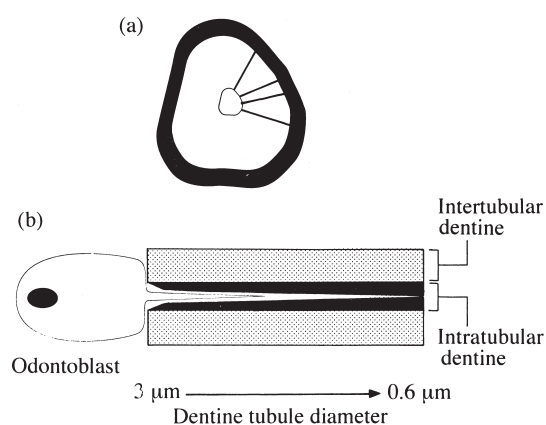
Etching the enamel surface produces a clean higher energy surface that is highly receptive to wetting. Attachment to the etched surface is established best using either an unfilled resin (the resin which forms the basis of the composite) or a *dentine bonding agent* (DBA). Although DBAs are designed to attach composite to dentine, they also bond well to enamel. Indeed, the bond strength of composite to etched enamel using a DBA as the intermediary layer is often greater than that when using a simple unfilled resin. It is essential to use an unfilled resin as the intermediary between etched enamel and the composite. Modern composites contain sufficiently small quantities of resin that they cannot wet the enamel surface adequately without the intermediary resin layer.

Etching a prepared enamel surface is relatively straightforward. If part of the enamel to be etched has not been prepared then it is necessary to extend the etching time. Enamel that has been exposed in the mouth has an amorphous mineralized layer on its surface as a result of intra-oral maturation. (This occurs as a consequence of the regular cycle of surface de- and re-mineralization associated with acids in diet and those produced as a consequence of intake of fermentable sugars. As a consequence the surface layers of enamel have high levels of trace minerals and fluoride, making them more resistant to etching, and are without a regular prismatic structure.) The same caveat applies to enamel on teeth that have recently erupted into the mouth where there is also an amorphous layer on the surface. Such amorphous layers need to be removed before the etching process can produce an appropriately microporous surface to achieve micromechanical retention at the enamel interface.

The high energy enamel surface produced by etching will also actively attract saliva and its contained protein. If an etched surface becomes contaminated with saliva then its surface energy is dramatically reduced and effective bonding with a resin system is prevented. The precipitated protein can be removed by further acid treatment of the enamel surface. The etching time required to remove such protein contamination is less than that required for initial enamel preparation (typically 15 seconds compared with 30 for treatment with 37% phosphoric acid).

### The bonding of composites to dentine

The reader is encouraged to refer to Chapter 23 of this book *before* undertaking any consideration of the clinical handling of bonding systems. Dentine has a very different structure to enamel. It has much higher levels of organic component with reduced mineral. In addition the structure and composition vary considerably as the dentine surface under consideration gets closer to the pulp. There are two reasons for the alteration in mineralization and structure. Dentine maturation is greater as the dentine gets close to the root surface or the amelodentinal junction. This results in increased mineralization of intertubular dentine and extensive deposition of intratubular mineral. This latter has the effect both of increasing local mineral content and altering the relative areas of mineralized dentine and patent dentine tubules. As the dentine gets closer to the pulp the mineralization of intertubular dentine decreases, as do the deposits of intratubular mineral. Furthermore, all tubules originate at the pulp and then radiate outwards towards the periphery of the tooth/root. Consequently, the tubule density per unit surface area of a cut dentine surface increases markedly the closer that surface gets to the pulp (Fig. 22.21).



**Fig. 22.21** The area of a cross-section of dentine occupied by dentine tubules is reduced as the dentine approaches the amelodentinal junction for two reasons: (1) The dentine tubules radiate outwards from the pulp (a) towards the enamel, reducing the number per unit area. (2) The diameter of the dentine tubule reduces dramatically as it progresses towards the pulp as the intratubular dentine increases in thickness (b).

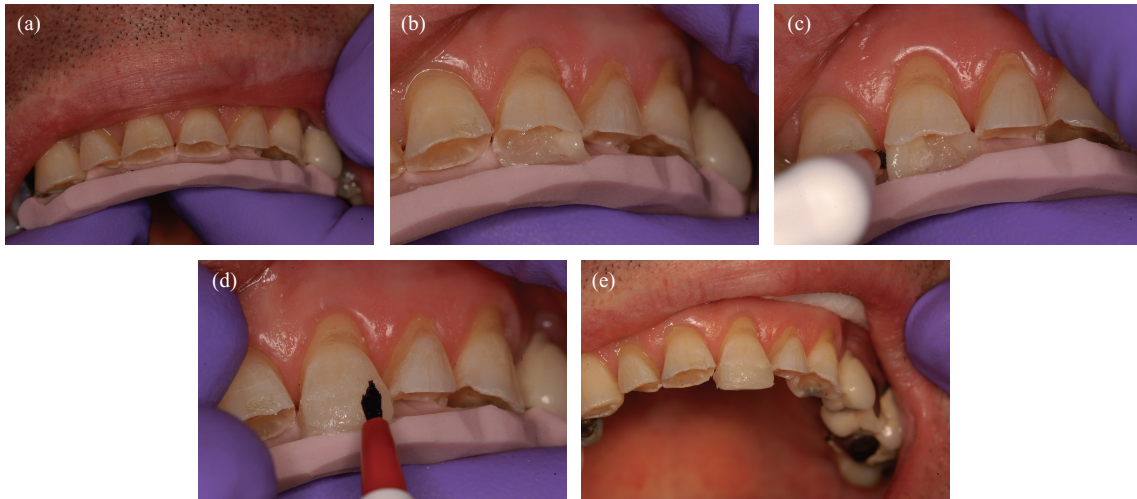
The bulk of the water that is contained in dentine is located in the dentine tubules, hence the water content of the dentine increases the closer to the pulp. All vital dentine contains some moisture and hence a hydrophilic resin (e.g. DBA) is required to achieve adequate attachment. The DBA can be designed to bond to either the organic or the inorganic elements of dentine, although the latter is more common. Current concepts of dentine bonding also include the creation of an interpenetrating resin structure with collagen fibres originating within the dentine becoming invested in resin to form the *hybrid layer*. Theories of bonding are covered in greater detail in Chapter 23.

In order to achieve bonding the surface of the dentine needs to be demineralized using an acid. This results in removal of the smear layer (a layer of loosely attached cutting debris from surface preparation) and then demineralization of the dentine, exposing collagen. Simultaneously the plugs of cutting debris that occlude dentine tubule openings are removed and the tubule orifice widened.

Care is required in handling this prepared surface to achieve reliable bonding. If the surface of the dentine is desiccated during drying the cavity the collagen network collapses, producing a dense mat of collagen fibres lying on the surface of the dentine. This collagen thatch is very difficult to penetrate with a resin to achieve bonding. Equally, if the dentine surface is too wet, even the hydrophilic resins used in DBAs cannot cope with the water volume and the DBA tends to form an emulsion with the water rather than displacing it. This emulsion cannot polymerise adequately and hence bond strengths are reduced. There is an optimum dampness of dentine which maintains an expanded collagen structure but at which level homogeneity of the DBA is maintained. The methods of achieving this optimum *in vivo* may depend on whether a *total etch* or *self etching primer* approach is being used but in principle are two-fold:

- (1) If the cavity is confined to dentine alone then the wet dentine surface should be blotted dry with cotton wool rather than air dried.
- (2) If there are both enamel and dentine surfaces involved there is a need to dry the enamel to check the quality of enamel preparation (well etched enamel has a *frosty* surface appear-





**Fig. 22.22** An example of the clinical technique used to place modern resin composite restoration. (a) A worn dentition with a matrix made from impression putty of a diagnostic wax-up of the desired clinical outcome to help guide composite placement. (b) The palatal and distal walls of 21 have been rebuilt using an 'enamel' composite. (c) 'Dentine' composite is used to build the core of the restoration in an attempt to reproduce the graded diamond burs and disks structure. (d) Surface contouring of the final 'enamel' composite layer, a stiff brush is a useful tool for shaping resin composite materials. (e) The final restoration with the matrix removed prior to polishing. With this approach it is not possible to produce a 'matrix finish' and the surface needs to be polished carefully with graded diamond burs and discs. This both improves the surface lustre and eliminates the oxygen inhibited layer from the surface of the restoration.

ance). The drying is likely to result in a formation of a collagen thatch. The dentine surface is then rehydrated with water before blot drying with cotton wool to achieve the required dampness. DBAs bond to damp enamel as well as damp dentine, so it is not of concern if the etched enamel is also moistened with water in this process.

Prevention of salivary contamination of prepared dentine surfaces is again important to ensure adequate bonding. For both enamel and dentine bonding the best way of achieving this quality of isolation is the use of a rubber dam. This can be difficult to place for cavities with deep subgingival margins. In this circumstance it may be possible to use a combination of cotton rolls and gingival retraction cord to control moisture. If it is not possible to control moisture contamination, particularly at the gingival extent of a cavity, then the operator should question seriously whether composite is the appropriate material to use for a given cavity. A lack of bonding of composite to enamel and/or dentine will result in a significant marginal gap forming and an associated risk of sensitivity and recurrent decay.

### *Material placement*

There are two considerations to be taken into account when placing composites in a cavity: maximizing quality of cure and minimizing the adverse effects of polymerisation shrinkage on the tooth. All currently available composites shrink on setting by between 1.5 and 3% by volume (depending on filler type and loading). The pattern of shrinkage and quality of cure depends upon the method of initiation of polymerisation (see above). In summary, chemically activated resins shrink towards their centre and will cure in bulk. Visible light cured (VLC) resins shrink towards the curing light and can only be cured in thin section. These latter properties can be exploited when placing VLC resins to help to maximize the chance of obtaining a marginal seal and minimize the effects of polymerisation shrinkage on tooth tissue by directing cure towards tooth/resin interfaces and placing the material in small increments. This is particularly appropriate and important for class II cavities, where material bulk is greater and tooth deformation associated with wall-to-wall polymerisation contraction has been implicated in causation of post-operative sensitivity.

### Maximizing quality of cure

It is necessary to place VLC resins in increments of not more than 2 mm in depth to ensure adequate cure using currently available curing units. The 2 mm cure depth is dependent upon the colour and translucency of the resin, the distance the light tip is away from the surface of the composite and whether or not the curing is being performed through another tissue (e.g. enamel or dentine). Incremental depths should be reduced for dark shades, where the light tip has to be some distance from the resin or when cure is being attempted through tooth tissue. One particular problem is achieving adequate cure at the base of the gingival floor of a class II cavity. Some light-curing units have interchangeable fibre-optic light guides with small tip diameters to allow the tip of the curing light to get as close as possible to the resin surface. Alternatively light-transmitting wedges can be used in conjunction with a transparent matrix band to direct light towards the gingival floor of the cavity and material present in that area. Fig. 22.22 shows a clinical sequence for placement of a modern 'aesthetic' anterior restorator where the composite, with varying colour and opacity, is used to simulate enamel and dentine. The multiple small increments are cured separately, maximising quality of cure.

### Minimizing the adverse effects of polymerisation shrinkage

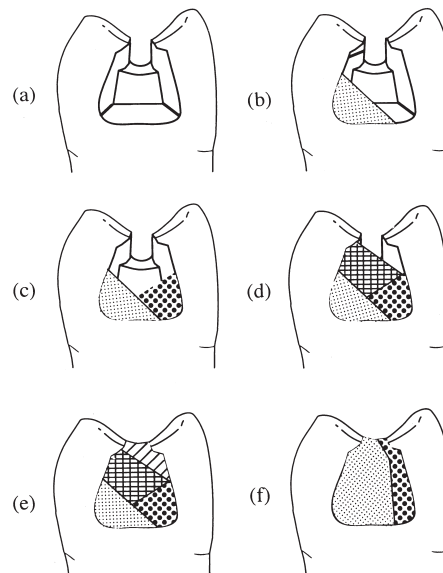
The adverse effects of polymerisation shrinkage include distortion of the tooth and failure to establish a marginal seal, both of which can result in postoperative sensitivity. Developments of low shrinkage materials (see p. 207) will reduce the damage caused.

*Incremental placement techniques:* The dimensional changes associated with polymerisation affect composite resins in two ways. Whilst the material remains plastic it will flow in association with contraction, whereas once a certain level of rigidity is achieved the material undergoes a formal shrinkage process. Plastic flow occurs towards *bound surfaces* (usually those where the resin is in contact with another material, e.g. enamel or dentine) and away from surfaces exposed to air. If a given volume of material is cured in increments then there are multiple oppor-

tunities for this plastic flow to occur. Hence, although the overall proportional shrinkage of the resin filling a cavity will be the same for bulk or incremental placement, more of that shrinkage will be taken up by plastic flow with an incremental approach. An explanation of this is given by consideration of the section on setting contraction (see Section 22.5).

There have been two techniques for incremental curing described, the herringbone and lateral filling methods (Fig. 22.23). Both techniques minimize the wall to wall effects of shrinkage.

*Directional curing techniques:* VLC materials start to cure at the surface closest to the curing light and then shrink towards that light. This can be used to help establish and maintain a marginal seal. At the base of a box, curing can be initiated by using a light-transmitting wedge to cure the increment closest to the cervical margins first. Curing of the remainder of the increment will then be undertaken from the occlusal aspect. When the herringbone approach is used the initial curing application of the curing light should be through the tooth from the lateral aspect if possible. This



**Fig. 22.23** Composites should be introduced into large cavities in increments to maximize quality of cure and help to reduce polymerisation stress. On completion of the cavity (a) composite is placed in the cavity in diagonal increments, producing a herringbone effect (b–e) to restore the defect. An alternative approach is a lateral incremental filling technique (f).



will establish the link between the composite and tooth before once again curing the bulk of the increment from the occlusal.

*Increasing the effective filler loading:* One of the principal methods of reducing polymerisation shrinkage in composites is to increase the relative proportion of filler to resin. Unfortunately there are practical limits in increasing the filler loading after which the material becomes so viscous that it cannot be handled clinically. It is, however, possible to increase the effective filler loading by incorporating either a pre-polymerised piece of composite into the restoration or by using commercially available quartz inserts to achieve the same effect. The logical extension of this approach is to make a composite or porcelain inlay and lute the inlay using a composite luting agent. Unfortunately there comes a stage where the geometry of the restoration negates the beneficial result of reducing the volume of resin undergoing a polymerisation reaction. This effect is associated with the configuration or C-factor, as discussed in Section 22.5.

#### *Matrix techniques and the establishment of proximal contacts*

A surface matrix has three benefits: (1) it helps to guide the formation of a peripheral profile of the restoration, (2) it isolates the resin from the atmosphere which helps to minimize the effect of air inhibition of cure of the resin at the surface and (3) the layer of material immediately adjacent to the matrix is resin-rich, producing a high gloss surface giving optimal appearance on placement.

Two materials are used to produce clear, flexible matrix structures for use with composites, cellulose acetate and polyester film (Mylar® or Melinex®). Cellulose acetate is thicker and more fragile than the polyester products. In addition there have been some suggestions that the plasticizer in cellulose acetate strips may cause some softening of the resin surface, making it more susceptible to early loss of resin and hence the high gloss matrix finish.

Matrixes for proximal cavities on anterior teeth should be placed between teeth after the enamel has been prepared for bonding but before the DBA or unfilled resin is applied to the prepared tooth tissues. If the matrix is not applied before

the DBA/resin there is a risk that the unfilled resins will flow between adjacent teeth, linking them together and making subsequent matrix placement difficult if not impossible. This approach applies even when an incremental build-up technique is being used, even though the matrix does not come into use until the increments begin to restore the peripheral contour of the tooth.

Transparent matrixes for cervical restorations are more difficult to use. Those that are commercially available are pre-formed to produce the buccal convexity of the root surface. They can exhibit some flexibility to allow them to adapt to different root contours. However, there remains a tendency for the matrix to 'fit where it touches' with an associated risk of producing marginal overhangs that need to be removed after the restoration has been cured.

Matrix techniques for proximal cavities on molar teeth involve placing a band around the tooth with some form of tightening mechanism. If a tooth only has one proximal box and the opposite surface is intact, forming a good contact with an adjacent tooth, it can be difficult to pass a transparent band through such a contact as the matrix material is relatively fragile. Pressing a wedge home between pairs of teeth in this position can help to separate the contact and facilitate band placement. Obviously, a transparent band is essential if the concepts of directional polymerisation described earlier are to be used. As a last resort a metallic matrix can be used, but it must be recognized that the ability to achieve a satisfactory marginal seal may be compromised as a consequence.

Obviously, when restoring a proximal surface it is desirable to establish an appropriate contact relationship between any adjacent tooth and the restoration. This can be a difficult task when using a composite as compensation has to be achieved both for the thickness of the matrix band itself and also for the shrinkage of the resin on setting. The use of a proximal wedge to help to hold the cervical extent of the band against the root face will help with this process as the wedge will tend to separate adjacent teeth and also extrude the teeth from their socket slightly. On removing the wedge the teeth will rebound into their original position, coming closer together in the process. Once the wedge is in place, it is essential to ensure that the matrix band is in contact with the adjacent tooth in the separated state, to optimize the

chance of a contact being achieved. One further possibility is to make a small pellet of pre-cured composite which can be wedged into the proximal box between the axial wall of the box and the adjacent tooth. Obviously this will not shrink on further polymerisation and hence will facilitate the formation of a contact.

### Finishing and polishing

Once material is placed, there will usually be a requirement for finishing and polishing in some form, either as a consequence of marginal excess or to define and refine the position and pattern of tooth to tooth contact. Composites can be finished immediately after placement using rotary cutting tools, burs, discs and strips. (Fig 22.24). Bulk changes in profile are best achieved using small particle size diamond burs, either in an airtor or a speed accelerating hand piece on a conventional motor (the latter accelerates the rotational speed by between 3 and 5 to 1, giving a burr speed of up to 120–200 000 rpm from a 40 000 rpm air or electromotor). These burs are delicate and should be used with care and with copious water cooling to prevent damage to the diamond abrasives. Such small particle diamond burs are produced in a variety of shapes and grit sizes of diamond. The basic principle of surface finishing – commencing with the large particle size abrasives and progressing downward in grit size – should be observed. Multi-fluted tungsten

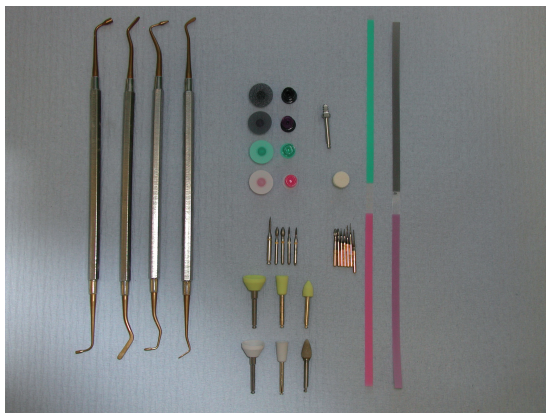


Fig. 22.24 Instruments and devices used for shaping, contouring and polishing composite filling materials.

carbide burs are an alternative to diamond abrasives. These have between 20 and 40 cutting blades as opposed to 6 or 8 for conventional cavity preparation instruments.

The ease of identification of cavity margins, particularly on the occlusal surface of molar teeth, during finishing will depend on the design of the enamel finishing line. Enamel margins that are finished at or close to a 90° angle are easier to identify than those that are prepared with a very marked marginal bevel. In addition such margins are less likely to develop marginal stain with time. (This is probably a reflection of the relative fragility of thin films of composite and their very different thermal properties compared to enamel on dentine.) The desirability for ease of identification of a margin and structural integrity of the periphery of the completed restoration given by marginal bulk must be weighed against the desire to achieve optimal bonding by etching enamel prisms perpendicular to their long axes. A finishing angle of about 120° gives a reasonable compromise between these two ideals.

Once bulk contour has been achieved using burs then finishing can continue with either disc-mounted abrasives or abrasive-impregnated rubber wheels, cones or points. There are a large number of commercially available systems for fine polishing of composite, some of which are material-specific and some more generic in nature. Once again, each system comes in a variety of abrasive particle sizes and the larger abrasive size should be used first. Polishing is achieved by gradually reducing the particle size of the abrasive. Some composite manufacturers recommend an abrasive paste in a slurry for final polishing.

The objective of polishing is to produce as smooth a surface as possible whilst maintaining the required morphology of the restoration. The quality of surface finish that can be achieved depends upon both the skill of the operator and the nature of the composite, as described in Section 22.5. Microfilled composites are inherently more polishable than those with larger/harder filler particles. One secondary benefit of the polishing process is an increased toughness of the surface layer of the composite. This is due to local heating when using rubber or disc-based abrasives without water cooling. The local rise in temperature often exceeds the glass transition temperature of the resin, producing some smearing of the resin surface with altered physical characteristics.

### Repair of composite restorations

One of the advantages of composite restorations is that it is possible to repair them in a fairly straightforward way by addition of further composite material. However, the strength of the union between old composite and new is relatively weak. There are three reasons for this:

- The matrix of the composite to be repaired has already been cured so there will be relatively few un-reacted double bonds on the surface of the resin to which the new material is to be attached. Consequently the link between old and new materials is relatively tenuous.
- The exposed surface of a cut or fractured composite resin comprises between 65 and 80% filler with the remainder as resin between the filler particles. There is the potential for some attachment between the old and new resin. However the exposed filler surfaces are unlikely to be coated in a silane coupling agent and as a consequence it is not possible for the resin in the new composite to bond to a significant proportion of the old composite surface.
- Resins that have been exposed in the mouth for periods of time take up water and swell. It is thought that it is more difficult to bond to a water imbibed surface and also stresses will inevitably be set up at the interface between old and new material as the new material also absorbs water with time in the oral environment and swells. Thorough cleaning of the resin surface to remove cutting debris helps to maximize attachment strength, as does the use of an intra-oral sandblaster to either roughen the surface or to silicoat the surface using a tribo-mechanical approach. More details of this technique can be found in section 23.9.

### 22.8 Applications of composites

Composite resins may be used as alternatives to silicate filling materials for the restoration of class III cavities. Other applications, such as the restoration of fractured incisal edges, depend upon the use of special techniques in which adhesion between restorative material and tooth substance is achieved. These are discussed in Chapter 23.

There is a growing tendency to consider composite resins for use as alternatives to amalgam in

posterior cavities. Materials are available which appear to match amalgam in terms of physical properties, however, the technique of placement for composites in posterior teeth, without incorporating voids, is difficult. In addition, the durability of composites appears to be inferior to that of amalgam, particularly in class II cavities where considerable loss of anatomical form can take place due to wear. For class I cavities, where the material is fully surrounded by enamel, the wear is less noticeable. Improvements in the quality of materials have to some extent overcome the problems related to wear resistance in that other factors such as chipping, ditching, fracture and leakage have become more noticeable.

There is some question over which group of composite materials offers the best chance of success in posterior teeth. Some clinical trials report encouraging results for microfilled composites after a year or two. However, many of the products offered commercially as alternatives to amalgam are hybrid materials, particularly the light-activated variety. Materials containing barium glass fillers or other fillers containing heavy metal atoms are most promising since they are radiopaque. They offer the practitioner the chance to confirm that the cavity has been correctly filled and also to check for the presence of caries in the surrounding dentine at subsequent examinations.

Good marginal seal is considered to be a major requirement of a restorative material in order to reduce or eliminate the chances of microleakage. The attainment of a good seal depends upon the formation of adhesive bonds between the restorative resin and tooth substance and upon minimal shrinkage of the resin during curing. In larger cavities the total amount of shrinkage is greater and the chance of maintaining a good marginal seal reduced. Class I and II cavities in molars and premolars may be large enough in some cases to cause significant stress to be placed on the tooth-restoration interface with a subsequent breakdown of adhesion, particularly at restorative-dentine margins. Inadequate marginal seal in large cavities is still considered a potential disadvantage of posterior composite materials, particularly when a seal to dentine is required. Adhesive materials and specialized techniques, including the so-called sandwich technique are discussed in Chapters 23 and 24.

*Composite inlays:* Another approach to overcoming the effects of shrinkage and the resulting micro-leakage that may occur is the use of *composite inlays*. The principle behind these is that the bulk of the shrinkage occurs before the material is finally seated into the prepared cavity using a luting resin. Two approaches are possible, using either a chairside technique or an indirect, laboratory-based technique. For the chairside technique, an inlay cavity is cut by the dentist and the walls of the cavity coated with a release agent. The cavity is then filled with a composite resin – a light-activated material would normally be used. After initial curing the inlay is removed from the cavity; a process which is facilitated by proper cavity preparation and the use of the release agent. At this stage an opportunity may be taken to enhance the properties of the composite material by subjecting it to treatment with intense light and heat or pressure and heat to increase the degree of polymerisation. The principle of this post-curing or annealing treatment is to heat the material to above the glass transition temperature of the resin in order to cause sufficient molecular mobility to allow further polymerisation and cross-linking to occur. This treatment has been shown to cause only a moderate improvement in hardness and flexural strength. Care must be taken not to induce an excessive amount of cross-linking as this causes the material to become more brittle. Hence, post-curing must be carried out under controlled conditions. The indirect approach is similar except that the inlay is formed on a model constructed from an impression. The composite inlay is seated back into the prepared cavity using a composite resin luting cement. Most cements used for this purpose are of the dual-cure variety. They have relatively low filler content giving the fluidity required to enable seating of the inlay. They set rapidly at the exposed margins when illuminated by a polymerization activation light but also undergo slow chemically activated polymerisation within the unexposed bulk. The completed inlay therefore consists of a bulk of well-polymerised composite material for which the margins are sealed by a thin layer of the luting

product. Only the shrinkage of the luting material can contribute towards marginal leakage gaps and the thin section of this material ensures that such gaps should be minimal. Although only a thin layer of luting resin cement is used, its shrinkage can result in a relatively large stress at the surface with both the tooth and the inlay due to the large C-factor which applies to this type of situation. The magnitude of the stress can be great enough to disrupt adhesive forces which may not have matured sufficiently to withstand the effects of shrinkage.

Another potential problem with composite inlays is related to the differential wear rates of the relatively hard inlay material compared with the relatively soft luting material. This is caused by a combination of the lower filler content and lower degree of polymerisation of the latter. It can cause the formation of a ditch around the inlay as the softer material is preferentially worn.

## 22.9 Suggested further reading

- Burke, F.J.T., Watts, D.C., Wilson, N.H.F. & Wilson, M.A. (1991) Current status and rationale for composite inlays and onlays. *Br. Dent. J.* **170**, 269.
- Davidson, C.L. & Feilzer, A.J. (1997) Polymerisation shrinkage and polymerisation shrinkage stress in polymer-based restoratives. *J. Dent.* **25**, 435.
- Ferracane, J.L. (1995) Current trends in dental composites. *Crit. Rev. Oral Biol. Med.* **6**, 302.
- ISO 4049 Dentistry: polymer-based filling, restorative and luting materials.
- Leinfelder, K.F. (1995) Posterior composite resins. *J. Am. Dent. Assoc.* **126**, 663.
- Leinfelder, K.F., Bayne, S.C. & Swift, E.J. Jr (1999) Packable composites: overview and technical considerations. *J. Esthet. Dent.* **11**, 234.
- Sakaguchi, R.L., Wiltbank, B.D. & Murchison, C.F. (2005) Cure induced stresses and damage in particulate reinforced polymer matrix composites: a review of the scientific literature. *Dent. Mater.* **21**, 43.
- Soderholm, K.J. & Mariotti, A. (1999) BIS-GMA-based resins in dentistry: are they safe? *J. Am. Dent. Assoc.* **130**, 201.
- Stansbury, J.W. (2000) Curing dental resins and composites by photopolymerisation. *J. Esthet. Dent.* **12**, 300.