

Adhesive bonding of composites

1. Introduction

Whilst forming an integral part of a wide variety of fabricated products, adhesives offer the potential to create new, challenging product designs. Structural and speciality adhesives account for about 30% of total adhesive and sealant sales, with uses in many industries:

- automotive
- aerospace
- domestic appliance
- biomedical/dental
- consumer electronics
- construction
- general industrial
- industrial-machine
- marine
- sports equipment

Synthetic adhesives have good adhesion to a variety of substrates, can be applied quickly, have many excellent properties, and can be cost-effective.

Advantages:

- provision of large, stress-bearing area
- excellent fatigue strength
- good shock absorption
- reduced galvanic corrosion
- no need to have access to far-side of adherend to make joint
- bonding is possible on dissimilar materials
- provision of smooth contours and sections around joint areas
- sealing
- improved damping which increases structural stiffness
- reduction in distortion and metallurgical changes due to low levels of heat required compared with welding
- good strength to weight ratio
- ability to join heat sensitive materials using room temperature curing materials

Disadvantages:

- surfaces will generally need to be cleaned and degreased
- significant cure-times may be required
- heat and pressure may be needed to cure an adhesive
- jigs and fixtures may be required to locate components whilst the joint cures
- rigid process control is required to obtain consistent results
- conventional non-destructive inspection of bonded joints is difficult
- adhesives will have a shelf-life and may require special storage conditions

- in relation to their good performance in compression and shear loading, adhesives have relatively poor resistance to tensile stresses caused by peel and cleavage forces
- adhesives have an upper temperature limit above which they will degrade

Why use adhesives?

Basically, to make money by offering better products. The exact combination of reasons will vary from case to case, but advantages should be sought in the following areas -

Reduced production costs may result from:

- Increased production speed

In comparison with other fabrication methods, adhesive assembly is essentially fast. Even if curing is required, this can often be accommodated 'off-line', or combined with other processing stages such as paint curing.

- Material selection

In contrast to welding, adhesives allow a wide freedom of choice during material specification. It is possible to mix and match material combinations to suit product function and save production costs in ways which have been impossible in the past.

Traditional materials may be combined with new metal alloys, plastics, composites, and ceramics to give distinctive product advantages.

Absorbing the full potential of this new freedom is perhaps one of the biggest challenges in finding significant market opportunities.

- Design for manufacture

Adhesive assembly offers significant cost savings if material costs can be reduced and production operations simplified. There is ample evidence that this can be the case if design and manufacturing functions co-operate to design or redesign the product with manufacturing in mind.

New approaches can be taken in the manufacture of sub-components: castings may be combined with extrusions, and sheet components and parts produced in a variety of other ways.

- Better production sequences

Traditional assembly methods such as welding impose fairly rigid sequences during production and frequently demand intermediate processing to remove contamination or rectify distortion.

Adhesives may be applied more flexibly within the production sequence: after finish painting, for instance. They allow new approaches to production planning, shop layout

and work-flow. Bottlenecks can be removed, unnecessary operations eliminated and work-in-progress reduced.

- Low capital costs

Many adhesive operations involve manual application and use of adhesive packages which have built-in applicators. Even when mechanised or automated application is justified for high volume work, the equipment is usually lighter than would be used for welding.

- Low production costs

This is a source of significant confusion. Costs 'per tube' of some adhesives may be high, but this should not be confused with all-in production costs or cost per product. Cost comparisons should be based on the costs of the whole joining process including plant, preparation and other pre-assembly costs, production and rectification expenses.

All-in cost assessments of this type provide a basis for accurate comparisons and adhesive assembly may often give significant benefits.

Design considerations

It is necessary to consider the following specific design topics in addition to all other aspects of adhesive technology -

- basic principles and rules
 - product and process design; strength of materials; design principles; basics of adhesive bonding design
- mechanical behaviour
 - stresses; joint geometries; analysis; joint dimensions; criteria; hybrid joints
- performance in-service
 - creep; fatigue; thermal; moisture; chemical; stress; combined effects; life prediction.
- manufacturing considerations
 - ease of assembly; value analysis; automation; costing and economics; quality assurance; robustness or mistake-proofing

Assembly considerations

How adhesives are applied and cured depends on:

- whether there is a facility to change the manufacturing process
- curing mechanism of the adhesive
- whether it is possible to heat-cure an adhesive
- time-factors in the assembly process

Adhesive can be applied by an automated robotic system, a bulk dispensing system or a portable hand-held dispensing cartridge which allows the system to be mobile. Adhesives can even be applied by hand with a spatula.

Which application method is chosen depends on the volume of adhesive being used. Regarding two-part epoxies and polyurethanes, mixing and metering of exactly the right amount of component parts is vital for optimum performance of the adhesive.

Equipment exists which can provide both exact metering and full mixing, as well as dispensing in exactly the right position for manufacturing the product. In heat-curing one-part paste or film adhesives, platens, autoclaves and vacuum presses may be required.

2. Adhesives

In simple terms, the sequence for making an adhesively bonded product is:

- select materials
 - design joint
 - select adhesive
- = design activities

- pre-treat surfaces
 - assemble
 - cure
 - final inspection
- = manufacturing activities

The bonding process requires consideration of all the following activities:

- Sourcing and storing adhesive system
- Adhesive application (metering, mixing, dispensing and control)
- Adherend preparation
- Assembly (order of assembly, environment, tooling)
- Cure (equipment and control)
- Inspection
- Repair
- Automation and robotics
- Factory layout
- Quality management
- Bonding co-ordination (equivalent to PrEN 719, welding co-ordination)

A wide variety of adhesives is available from a range of adhesive manufacturers. It has been estimated that, world-wide, there are 250,000 adhesive grades available from 1,000 suppliers. However, it is possible to simplify the choice by (a) appreciating the basic types of adhesive, and (b) applying selection principles with key deselecting questions.

Major classes of adhesive

Adhesives can be classified by several methods, none of them perfect, such as the way they set (that is, transform from a wetting liquid to a load-bearing solid), the way they are used in assembly, or by chemical type.

The strongest adhesives set by chemical reaction. Less strong types harden by physical change, cooling from a melt or evaporation of a solvent. The major classes are described below.

Anaerobics

Anaerobic adhesives cure when in contact with metal, and the air is excluded - for example, when a bolt is home in a thread. They are often known as 'locking compounds', being used to secure, seal and retain turned, threaded, or similarly close fitting parts. They are based on synthetic acrylic resins.

Cyanoacrylates

Cyanoacrylate adhesives cure through reaction with moisture held on the surface to be bonded. They need close fitting joints and usually solidify in seconds. Cyanoacrylates are suited to small plastic parts and to rubber. They are a special type of acrylic resin.

Toughened Acrylics

Toughened acrylics are fast curing and offer high strength and toughness. Both one-part and two-part systems are available. In some two-part systems, no mixing is required because the adhesive is applied to one substrate, the activator to the second substrate, and the substrates joined. They tolerate minimal surface preparation and bond well to a wide range of materials.

Epoxies

Epoxy adhesives consist of an epoxy resin plus a hardener. They allow great versatility in formulation since there are many resins and many different hardeners. Epoxy adhesives can be used to join most materials. Epoxies have good strength, do not produce volatiles during curing and have low shrinkage. However, they can have low peel strength and flexibility and are brittle. Epoxy adhesives are available in one-part, two-part and film form and produce extremely strong durable bonds with most materials.

Polyurethanes

Polyurethane adhesives are chemically reactive formulations which may be one-part or two-part systems and are usually fast curing. They provide strong impact-resistant joints and have better low-temperature strength than any other adhesive. Polyurethanes are useful for bonding glass fibre reinforced plastics (GRP). The fast cure usually necessitates applying the adhesives by machine. They are often used with primers.

Silicones

Silicones are not very strong adhesives but are known for their flexibility and high temperature resistance. They are available in single or two-part forms. The latter function like the two-part epoxies, the former like the single-part polyurethanes. When the single-part adhesives cure they liberate either alcohol or acetic acid (the familiar smell of vinegar).

They are often used as bath and shower sealants. Their adhesion to surfaces is only fair but, like their flexibility, their durability is excellent. The two-part versions need a hardening agent to be mixed into the resin. Two forms are available - those which liberate acid on curing and those that do not. As might be anticipated, the two-part adhesive systems give a better cure in thick sections than do the single-part types.

Phenolics

Phenolics were the first adhesives for metals and have a long history of successful use for joining metal to metal and metal to wood. They require heat and pressure for the curing process.

Polyimides

Polyimides are mainly used in applications which exploit their ability to withstand temperature up to 350°C. They are available as liquids or films and although they have good strength retention at high temperature, they have the disadvantage of being expensive and difficult to handle.

The following adhesives undergo a physical change and are less effective at forming an adhesive bond.

Hot-melts

Hot-melts are based on modern thermoplastics and are used for fast assembly of structures designed to be only lightly loaded.

Plastisols

Plastisols are modified PVC dispersions which require heat to harden. The resultant joints are often resilient and tough.

Rubber Adhesives

Rubber adhesives are based on solutions of latexes and solidify through loss of the solvent medium. They are not suitable for sustained loadings.

Polyvinylacetate (PVAs)

Vinyl acetate is the principal constituent of the PVA emulsion adhesive. They are suited to bonding porous materials, such as paper or wood, and to general packaging work.

Pressure-sensitive adhesives

Pressure-sensitive adhesives are suitable for use as tapes and labels and, although they do not solidify, are often able to withstand adverse environments. This type of adhesive is not suitable for sustained loadings.

Adhesive selection principles

Selection of an adhesive for a particular application may at first appear daunting. However, there are many sources of assistance, such as adhesive suppliers, expert consultants and computer-based selection systems. Since none of these sources can be comprehensive, there are some guiding principles which will help in any decision-making process.

The joint type, joint function, in-service conditions and manufacturing issues must all be considered. But by defining a few key performance or manufacturing requirements, this will quickly deselect most potential adhesive types. Key deselecting questions may be one or more of the following:

- maximum allowed cost?
- bond-line thickness or gap filling ability?
- maximum or minimum continuous temperature performance?
- mechanical performance required - for example, shear strength, extension?
- required open-time before cure?
- cure speed?
- tolerant of contaminated surfaces?
- required form of adhesive - for example, film, paste, liquid, one-part?
- special property required - for example, electrical, thermal, optical?
- specific approval required - for example, fire rating, Mil-spec., FDA, medical?
- acceptable for site health & safety policies?

Development of adhesive selection software

Computer software has been developed to help with the complex and time-consuming task of adhesive selection. Resources available through TWI include:

- **The Adhesives Design Toolkit** - a free access website with information about adhesives and an adhesive selection module - www.adhesivestoolkit.com
- **Adhesive Technology** - a training CD-ROM which covers key topics including adhesive selection.
- **EASel (Engineers Adhesive Selector)** - a low cost, Windows-based software package for selecting the correct generic adhesive type for a particular application.

Types of adhesive – more details

Amino or urea adhesives

These are usually two-part systems consisting of resin and hardening agents and based on products from the reaction of urea and formaldehyde. Curing is normally achieved under pressure but without heat, although heating can be used to accelerate the cure. As the adhesive cures, water is liberated and this tends to limit their use to porous substrates. Due to their poor environmental resistance they are normally used in the manufacture of interior wooden structures.

Anaerobic adhesives

A member of the acrylic family of adhesives, they are based on modified acrylate acid di-esters, otherwise known as polyester-acrylic monomers. They are essentially thin, monomeric liquids, although they can be formulated into pastes or thixotropic liquids. They are single-part adhesives which cure when air is excluded, hence the name anaerobic.

Solely under the influence of anaerobic conditions the cure rate is quite slow; in the presence of metal the cure rate is much faster and this, in practice, is how they are used

- confined between closely fitting metal parts. The close fit excludes air and the metal surface speeds the rate of cure to a commercially useful degree.

Since hardening only takes place in the absence of air, these adhesives have the advantage that material outside the joint does not normally cure and hence can be wiped off after the assembly has reached handling strength. They are unique among adhesives in that they are made with different strength characteristics ranging from relatively weak materials, which allow the easy dismantling of large parts, to very strong materials for permanent fixing.

This variation in strength is brought about by a combination of the basic monomer chosen and the addition of varying amounts of plasticiser. Within each strength-band there will usually be several products of different viscosities, allowing different gaps to be filled at the same level of controlled strength. They can also be toughened (see later) to provide greatly improved peel and impact values.

Anaerobic adhesives are often known as 'locking compounds', being used to secure, seal and retain turned, threaded, or similarly close fitting parts. They are also used to bond coaxial assemblies and seal flange-faces.

Cyanoacrylate adhesives

While they constitute the second member of the acrylic family, these materials are different in nature from the anaerobic adhesives. They are still based on acrylic monomers but, due to quite major differences in the structure of the molecule, a different cure mechanism operates. The cyanoacrylate monomers are inherently unstable, so much so that, when spread thinly on a substrate, they will begin to polymerise almost instantly.

The process is started by the film of moisture found on most surfaces which is usually slightly alkaline and it is this alkalinity which causes the polymerisation. The rate of cure is fast, due to the ionic nature of the process. Most other adhesives involve either the direct chemical reaction of different species, e.g. epoxy and amine, or use a radical to initiate polymerisation e.g. acrylic. In both cases these methods of curing are slower because of the more complex nature of the interaction which needs to take place.

Because of the cyanoacrylate's need for slightly alkaline conditions, any acidic surfaces, such as wood, will tend to inhibit the cure and in extreme cases prevent curing altogether. However, the speed of cure and applicability on most surfaces, including human skin, has resulted in the universal generic name of 'superglues'. Most grades are low viscosity liquids and therefore they need close fitting joints. Newer developments of gelled variants allow cure in wider gaps and application to vertical surfaces. Cyanoacrylates are suited to small plastic parts and to rubber bonding.

Emulsion adhesives

This large class of adhesives is based on polymers such as polyvinyl acetate (PVA), acrylic, rubber or polyurethane. PVAs are familiar as the household glues which bond paper, cardboard and wood, these adhesives cure by loss of their fluid carrier, in this case water. The polymer, dispersed in the water, separates out as a sticky mass which gives good initial tack and then dries to a strong film which bonds the substrates

together. The rate of cure is controlled by the speed with which water is lost and generally, to obtain sound joints, one of the substrates must be absorbent.

Alternatively, the water is driven off completely before the joint is closed. Two such coated surfaces will bond immediately, in the case of rubber-based contact adhesives. Alternatively, the adhesive can be designed to be reactivated by solvent, heat or to be pressure-sensitive (see later).

Epoxy adhesives

This group of adhesives is widely used and is also one of the most diverse in terms of variants available. In the unhardened state, the chemical structure, from which the epoxy adhesive gets its name, is characterised by the ring-like shape of the epoxide group. All epoxy adhesives contain two or more of these groups per molecule of adhesive.

Although they are all similar in this respect, the form in which they are available varies widely, from low-viscosity liquids to solid pastes or films. The wide variety of basic epoxy resins, in combination with over 70 different curing agents - ranging from simple amines to complex anhydrides - give the group its diversity.

Throughout all the variations, the mechanism of curing is always the same. The ring structure is broken by an active molecule - typically an amine - and the two monomers link. The constant repetition of this process hardens the adhesive by forming a polymeric network. This mechanism requires exact quantities of resin and hardener, hence the need for precise mix-ratios and the thorough mixing of resin and hardener in two-part systems. Without these, the polymer will not form correctly and often inferior properties will result - typically lower strength and reduced environmental resistance.

Single-part epoxy adhesives are also available, in liquid, paste or film form. The resin and catalytic hardener are pre-mixed but polymerisation does not occur because the catalyst is in an inactive form at room temperature. It only becomes reactive towards the epoxide group as the temperature is raised, usually at a temperature in excess of 100°C. The higher the temperature, the faster the reaction becomes and hence shorter curing times are obtained. Cure of the two-part adhesives can also be accelerated by heat.

These materials have good strength and chemical resistance, do not produce volatiles during curing, and have low shrinkage. Therefore they form extremely strong and durable bonds with most materials in well designed joints. Development of toughened formulations (see later) has dramatically increased the demanding uses of these adhesives in many industries.

High temperature adhesives

Few adhesives are suitable for prolonged use at temperatures above 200°C. For specialist aerospace and electronic applications, in cases where brittle ceramic adhesives are not appropriate, then more exotic, synthetic polymers must be considered. Polyimide and bismaleimide adhesives are the most established types in this class. They are available as liquids or films, but are relatively expensive and difficult to handle. However, they are superior to most other adhesive types with regard to long-term strength retention at elevated temperatures.

Hot-melt adhesives

These are thermoplastic bonding materials applied as a melt - a hot and usually viscous

liquid - which cools and develops strength by its consequent solidification. The formulation of a hot-melt can be quite complex, based on polymer resins such as ethylene vinyl acetate (EVA), polyamide or polyurethane. High tack is needed to 'grab' the substrate, and thermal degradation of the melt must be suppressed. Some products, based on polyurethane technology, are also formulated to react with atmospheric moisture, which improves their heat and moisture-resistance (reactive hot melts).

The strength obtained from this class of adhesive is often modest and they are likely to fail in demanding environments - creep under warm conditions being a particular problem. The new moisture-reacting types are better. Hot-melts find extensive use in fast assembly of structures designed to be only lightly loaded. Their chemical composition means that they can be used to directly bond some plastics with low surface energy, e.g. polypropylene, which with other adhesive types, require a surface pre-treatment.

The term hot-melt can also apply to a technology where pressure-sensitive adhesives, elastosols (see later) or single-part epoxies can be deposited by this method.

Phenolic and resorcinolic adhesives

Phenolics were the first structural adhesives for metals, and have a long history of successful use for joining metals and wood. Although the starting materials used to make the two adhesive types in this group are different, they are chemically similar and the curing mechanism is the same. Consequently they can be considered together.

Initially, either phenol or resorcinol is part-reacted with formaldehyde to form the 'as supplied' adhesive. In use, the latter is fully cured by heating and, possibly, adding a catalyst. Water is liberated as the reaction proceeds. This means that either the substrates must be porous or a high pressure must be imposed to prevent the formation of voids. The brittle, basic resins can be modified with other more rubbery polymers (to give vinyl or nitrile phenolics).

These types of adhesive are particularly durable to both elevated temperatures and harsh environments and would see much greater use in engineering industries if they were easier to use and less susceptible to shock.

Plastisol and rubber adhesives

These adhesives take the form of viscous, immobile pastes which cure by a combination of solvent loss and chemical reaction. Plastisols consist of a suspension, or partial solution, of polyvinylchloride (PVC) particles in a combination of solvents, plasticisers and reacting monomers. After application, some solvent evaporation may be allowed before the joint is closed. On heating to about 180°C, the PVC dissolves in the plasticiser and reacts with any monomers present to form a cross-linked, semi-thermoset material. Once cooled to room temperature, a tough, flexible and durable bond is formed.

Very often plastisol adhesives were used in combination with spot welding, which took place through the film of unreacted adhesive. Welding holds the parts together during the heating cycle. However, local burning of the plastisol releases hydrochloric acid which can, and often does, initiate corrosion. A more recent variation avoids this problem by replacing the PVC with a crosslinkable butadiene polymer (Elastosol).

Polyurethane adhesives

These adhesives, often abbreviated to PU or PUR, which get their name from the chemical form of the hardened material, are another example of a two-part, chemically curing adhesive, and their reaction is very similar, in principle, to that of the epoxide.

The two components are mixed in exact proportions. Curing takes place by the reaction of alternating polymers containing alcohol or isocyanate groups which form urethane linkages in the final polymer. They are available in a variety of forms, depending on the use required. The adhesive depends upon the isocyanate group for its high level of reactivity.

By comparison, the epoxide group is less energetic. As a consequence, the curing of two-part polyurethanes is much faster than that of most epoxy adhesives. Single-part formulations are available, which are partially polymerised and stable until cure is initiated by the action of absorbed atmospheric moisture. Their reaction rate is slower because it takes time to absorb the necessary water. Polyurethanes can be supplied as reactive chemicals, solvent solutions, pastes or hot melts.

They provide strong, resilient joints which are impact resistant and have good low-temperature strength compared with many other adhesives. Polyurethanes find major uses in the bonding of glass fibre reinforced plastics (GRP), direct glazing of automobiles and lamination of both insulation panels and flexible packaging materials.

Pressure-sensitive adhesives

This large group of adhesives uses many polymers (acrylics, rubbers, polyurethanes), together with plasticisers and tackifying resins to form a permanently tacky (sticky) adhesive. They can be deposited from solvents, water emulsions or hot melts and find uses in stationery, labels, laminated products and as the active ingredient in pressure-sensitive tape adhesives (see later).

The name comes from the fact that moderate pressure alone is sufficient to spread the viscous adhesive layer on to the surface and achieve useful adhesive strength. Although they do not solidify or chemically cure, they are often able to withstand adverse environments. This type of adhesive is generally not suitable for sustained loading.

Radiation-cured adhesives

Adhesives in this class become active and cure when exposed to radiation, usually ultra-violet (UV) light. The mechanism depends upon special modifications to the monomer's structure and the inclusion of light-sensitive compounds which start the reaction.

Generally, they consist of acrylic monomers, but some UV-cured epoxies are now available, as well as special acrylics cured by certain visible light frequencies. They are widely used for bonding glass and transparent plastics. Alternatively, UV light can be used to rapidly 'tag' the edge of an opaque joint, with the cure completed thermally or by a two-part reactive system.

Silicone adhesives and sealants

While not very strong, these adhesives are known for their flexibility, good chemical and high temperature resistance. A combination of properties is achieved by the use of both organic and inorganic chemistry. As the name suggests, the main part of the adhesive is

based on silicon which has been reacted with oxygen and carbon to form a polymer. The presence of the silicon-oxygen link in the polymer chain, which is chemically more stable than the equivalent carbon-carbon link, gives these adhesives their high temperature resistance.

They are available in single or two-part forms. The latter function like the two-part epoxies, the former like the single-part polyurethanes. When the single-part adhesives cure, they liberate either alcohol or acetic acid (the familiar smell of vinegar). They are often used as bathroom or construction sealants.

Their adhesion to surfaces is only fair and is often improved with reactive primers, but like their flexibility, their durability is excellent. The two-part versions need a hardening agent to be mixed into the resin. Two forms are available; those which liberate acid on curing and those which do not. As might be anticipated, the two-part adhesive systems give a better cure in thick sections than do the single-part types and are often used in more demanding applications.

Solvent-based adhesives

This is a very large group of adhesives which all consist of a polymeric resin dissolved in an organic solvent. The adhesives are often based on rubber, but other plastics may be employed, such as acrylic, polystyrene or PVC. In use, the solvent is allowed to evaporate from the surfaces to be bonded before the joint is made. A well-known example is rubber-based contact adhesive. For safety and environmental reasons, water-based emulsions of similar polymers, or in some cases hot melts, are replacing these adhesives in many applications.

Tape adhesives

'Sellotape' or 'Scotchtape' are the familiar domestic examples of this group. All forms are based on a backing material, such as cellulose, polyester or PVC, which has been coated with a pressure-sensitive adhesive - a tacky, semi-solid polymer, either acrylic, polyurethane or rubber. Some have a separate release strip, while others do not.

Double-sided tape has been coated on both sides and must have a release strip. The central core can either be a thin plastic film (as above), a foamed plastic layer (to allow for movement or irregular bondlines), or nothing (a transfer tape). Generally, most pressure-sensitive tapes give high tack but fairly low strength. Some versions develop higher strength upon ageing. Newer, higher strength products can be used in more rigorous applications, previously the domain of reactive, curing adhesives.

Toughened adhesives

Almost all the reactive, chemically curing, high-strength adhesives suffer from some combination of low peel strength, impact, or environmental resistance. Although the situation can be improved by the use of plasticisers, there is usually a consequent loss of shear strength.

The basic problem is the brittle nature of the polymers which are normally formed when the high-strength adhesives are created. Once a crack starts in such a polymer, it grows very quickly and disintegration follows. The situation can be eased by using a variety of techniques to make the material more flexible, but this tends to reduce strength and environmental resistance.

During the last 25 years a process known as 'toughening' has been extensively developed using methods evolved earlier by the plastics industry. A toughened adhesive has small, rubber-like particles dispersed throughout the glassy matrix. The profound effect of these particles is to change the mechanical response of the adhesive and make it much more resistant to crack propagation. So far, this technology has only been successfully applied to the acrylic and epoxy-based adhesives.

The epoxy and anaerobic versions of acrylic adhesives were the first types to be toughened by this technique and the resulting adhesives have similar shear strength but greatly improved peel and impact values. The development of toughening has allowed adhesives to be used in more demanding conditions and, as a consequence, in a greater range of industries, particularly where load-bearing joints are required.

Toughened acrylic adhesives

'Toughened acrylics' were developed as an extension of earlier work on the single-component, anaerobic adhesives. The use of an initiator, in addition to the adhesive, made a higher level of performance possible. The initiator is applied to one surface and the adhesive to the other. When they are brought together, as the joint is closed, the initiator dissolves in the adhesive and the polymerisation reaction starts.

Although two components are required, the early versions of these adhesives did not require mixing prior to application. However, as a consequence, they did not cope well with large gaps. Newer acrylic adhesives, developed to fill gaps, are two-part, pre-mixed systems and some confuse the classifier by combining acrylic reactive monomers with epoxy or polyurethane pre-polymers. The cure can be accelerated by the application of heat.

Toughened acrylics are relatively fast curing and offer high strength and toughness, plus more flexibility than common epoxies. They tolerate minimal surface preparation and bond well to a wide range of materials.

Water-based adhesives

Adhesives which are applied when dissolved in water, include natural products such as starch, dextrin, casein or gelatin, and synthetic polymers including polyvinylpyrrolidone (PVP). Casein is obtained from milk and was one of the first adhesives used for bonding wooden aeroplane components. Starches and dextrans are still used in high volume, e.g. to bond cigarette papers and corrugated cardboard, respectively. PVP is used by most of us in the office and home as the main ingredient in 'Prittstick'.

These adhesives provide modest strength compared with most other types, but they form a vital component in rapid manufacturing processes which are devised and controlled to very high engineering standards. They can be used as intentionally temporary joints in specialist applications. An additional benefit in the current age of environmental consciousness is that many of this class of adhesives are obtained from renewable resources, do not inhibit biodegradation or prevent recycling.

3. Joint Design

Joint designs which are perfectly suited to other joining methods may be quite unsuitable for adhesives, and vice versa. The first part of this Section gives a brief guide to key

design considerations and provides details of various joint configurations used in adhesive bonding.

The author wishes to thank Bill Lees of Permabond for permission to use the illustrations included in this section of the best practice guide.

Strength of joints

Figure 3.1 shows the loading definitions used in this Best Practice Guide. In adhesive joints, load may be taken in shear, compression, tension, peel and/or cleavage. Load in peel and cleavage should be minimised by applying the principles of good joint design.

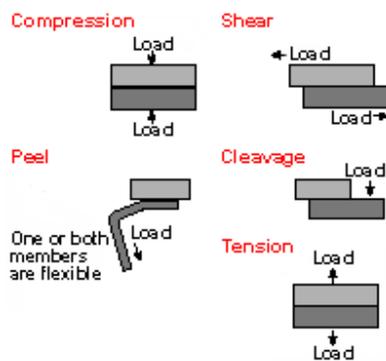


Fig. 3.1 Definitions of load

Adhesives should preferably be loaded in compression and shear, so as to minimise peel or cleavage forces in normal or accidental use. Even the best of the latest generation of toughened adhesives can carry loads roughly 100 times greater in standard shear tests than they can in peel. While such tests are not directly comparable, they show that even small peel loads are particularly destructive.

In contrast, compression loads are readily borne. If the forces are compared, then the relative ability of a joint to withstand compression, shear and peel loading is of the order of 1000:100:1. With peel and cleavage designed out, the main consideration in joint strength is shear, as in the lap joint.

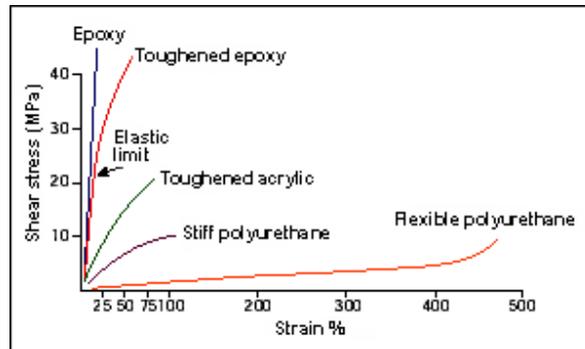


Fig. 3.2 A lap joint

A typical lap joint is shown in Figure 3.2. When bonding thin sheet materials, the capability of a joint to take load in shear does not increase progressively with joint area because the load-carrying ability is limited by maximum stress at the leading and trailing edges of the joint; this applies much less to thick adherends. Only a very small portion of the load is carried by any part of the joint more than 15mm from the edge normal to the load, unless very flexible adhesives are used.

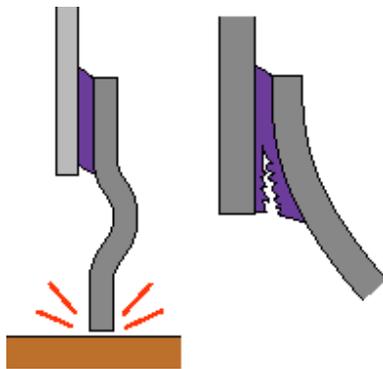
Fig. 3.3 Stress vs strain, for various adhesive types

The cohesive strength of the adhesive itself plays a key part in the overall strength of a bonded joint. Figure 3.3 shows the stress/strain relationships of a range of structural adhesive types.



Induced shock loads

A bonded assembly which is subjected to shock loading, induced by accidental impact or as a performance requirement, can fail as a result of cleavage or peel forces (Fig. 3.4).



In these cases it is important to maximise peel and cleavage resistance by selecting an adhesive with high impact strength or, if a brittle adhesive must be used, by joint design or additional mechanical fixing.

Fig. 3.4 Cleavage or peel due to shock (or static) loading

Adhesive layer thickness & control

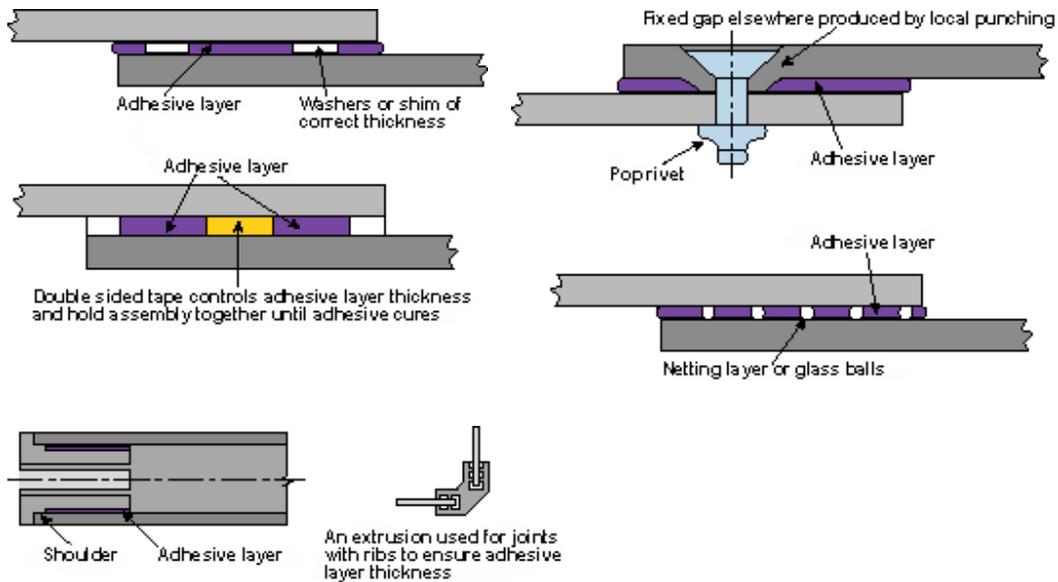
The maxim *'the thinner the adhesive line the better the joint'* is not true in all cases. If applied too zealously by a literally-minded bonder, it can lead to a joint starved of adhesive. Conversely, very thick bond lines, in particular when used with thin adherends (for example, 1mm thick), can result in load offset, higher peak stresses and reduced strength of sheet bonding.

Anaerobic acrylic adhesives are chemically formulated to polymerise fully in gaps of different size.

High performance epoxy adhesives will perform best at bondline thicknesses between 0.05 and 0.1mm. At thinner bondlines, there is insufficient adhesive to perform well in demanding situations such as preventing crack growth in fatigue loading.

Figure 3.5 shows several methods for controlling bondline thickness.

Fig. 3.5 Suggested methods to control adhesive layer thickness



Joint configurations

Lap joints

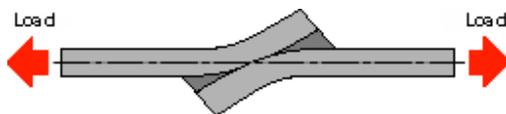


Fig. 3.3.6 Peel forces in a lap joint

In lap joints, initial loading is carried in shear along the line of the joined components. As load is increased, the joint becomes progressively distorted and peel forces come increasingly into play at the ends of the overlap as shown in Figure 6. In addition, tensile loads become significant across the joint. Failure occurs when:

- the adhesive fails - cohesive failure of the adhesive
- the adhesive fails at the surface of one of the joined parts - adhesive failure
- one of the joined parts breaks - parent material failure of the component since the component is not strong enough away from the joint.

Improvements to lap joint design

Suggested methods to modify basic lap joints are shown in Figure 3.7. They can reduce peel stresses by preventing the end of the overlap from lifting and hence allowing more load to be carried in shear before failure of the joint.

Further modifications to lap joint design can increase strength further, as shown in Figure 3.8.

Fig.3.7 Modifications to basic lap joint designs

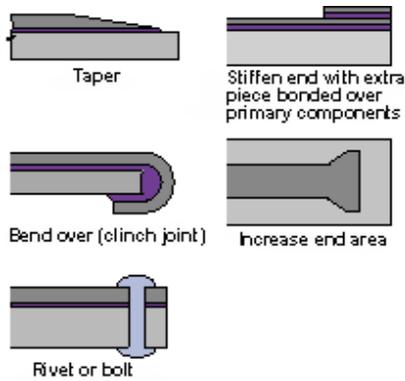
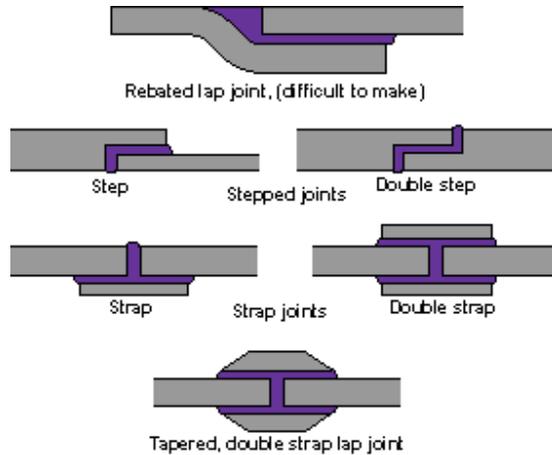


Fig. 3.8 Further modifications to lap joint design



The rebated lap joint is more resistant to peel and cleavage ensuring very robust joints.

Stepped lap joints are used where shaping and forming costs are low. Their use on metal structures is limited by machining costs.

Strapped butt joints are simple, cheap and effective, but have low resistance to peel and cleavage forces in one direction of bending and are difficult to assemble.

The double strap joint is very strong, but it is difficult to control the bond line thickness. If the straps are extruded the cost can be reasonable and joint details can be included to control the adhesive layer thickness.

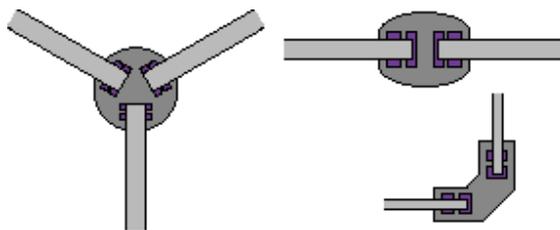


Fig. 3.9 Joints manufactured with the aid of extrusions

Maximum improvement can be obtained with the tapered double strap lap joint, but as discussed above, the bond line thickness is difficult to control.

Additional enclosed joint details can be generated, with regulated joint thickness, using proprietary extrusions and three typical examples are shown in Figure 3.9.

Cylindrical parts

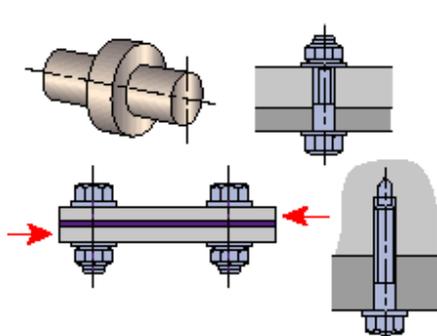


Fig. 3.10 Cylindrical, threadlock and surface jamming

The advantages of adhesive bonding techniques for assembly of shafts and associated components, as shown in Figure 3.10, can be summarised as follows:

- cracking due to excessive stresses in interference-fitted parts is avoided
- fitting of parts is almost invariably achieved more readily and more economically
- expensive grinding is usually not necessary
- compared with shrink and interference-fitted parts, bonded components in cylindrical designs extend the area engaged from about 20 per cent of that available to the maximum - the joint is sealed and fretting and associated corrosion are reduced
- accurate alignment (particularly angular) of bushes and bearings is better and easier to achieve
- stress characteristics of bonded joints are invariably more uniform than those in interference-fitted assemblies
- slip-fitted and bonded parts require minimal skill and equipment for assembly which, as a result, is usually quicker and invariably more economical
- soft metals and their alloys are retained better by adhesive than by friction
- stress-free assembly improves general dimensional accuracy and reduces distortion
- worn or badly machined parts may be readily restored to their correct dimension or alignment, by bonding with an appropriate self-aligning sleeve or shim (Fig. 3.11).

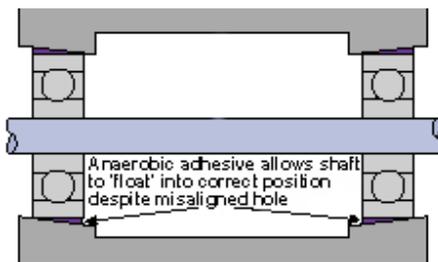


Fig. 3.11 An example of easier alignment by the use of adhesives

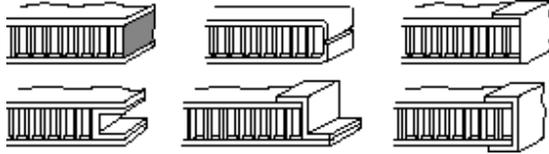
Honeycomb joints

Honeycomb sandwich panels are only possible through the use of film adhesives to join skins (usually aluminium or polymer composite) to the core (usually aluminium). They can provide relatively light and stiff panels for a variety of applications. Special techniques must be considered in fabricating with these materials, as shown in Fig. 3.12.

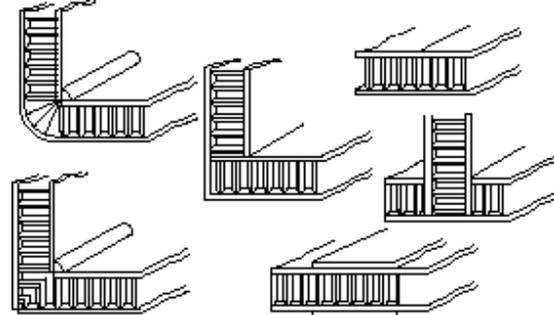
Edging techniques for honeycomb panels are shown in Fig. 3.12a. Flat panel joints and corner details can be generated as shown in Figure 3.12b. Extrusions are also convenient, as in Fig. 3.12c. When fasteners have to be attached to honeycomb panels, inserts can be bonded, the surrounding honeycomb cells often being filled with a paste adhesive or crimped into the panel (Fig. 3.12d).

Fig. 3.12 Joining of honeycomb materials

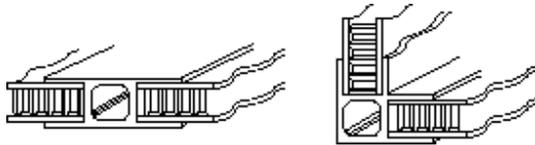
a) Typical flat panel edging methods



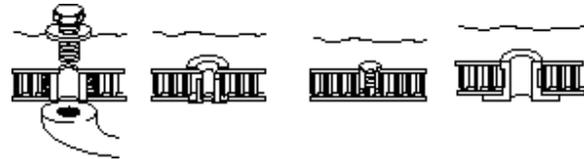
b) Typical flat panel joints and corners



c) Typical use of extrusions



d) Typical fastening methods (inserts)



Butt joints

Butt joints must be considered carefully, or avoided. Materials being joined and component geometry greatly influence the degree of success.

Typical forms of butt joint are shown in Fig. 3.13. Unless at least one of the joined parts is flexible, assemblies a) and b) will fail readily as even minor misalignment will induce very high peel and cleavage forces which will rupture the joint.

Reducing height (lower cleavage forces) and increasing diameter (increased area loaded in tensile mode) as in c) will improve the joint's performance. Alternatively, tongue and groove details can convert a butt joint into a design with significant elements in shear loading (Fig. 3.14).

Fig. 3.13 Typical forms of butt joint

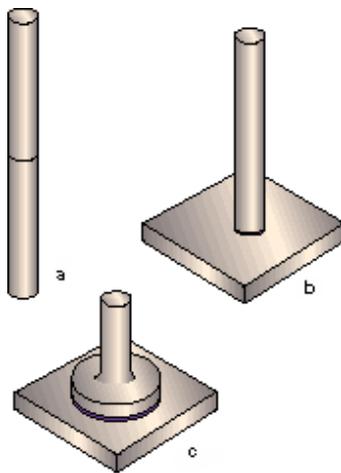
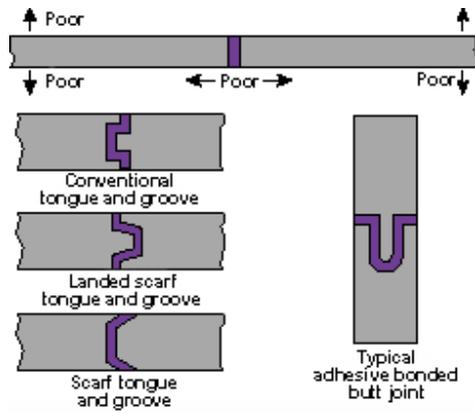


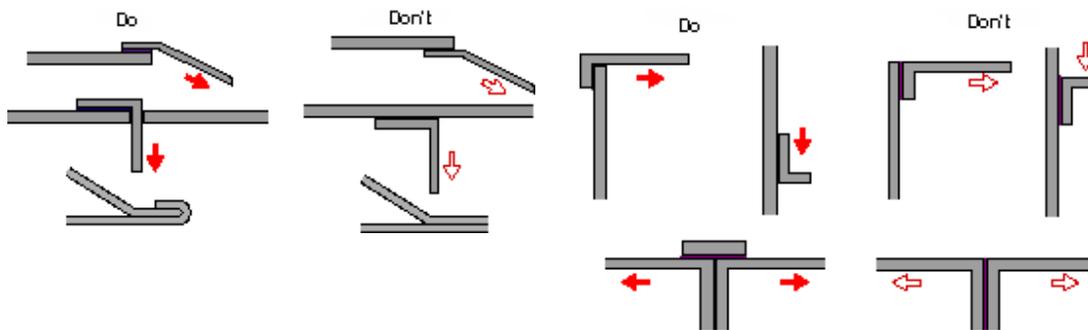
Fig. 3.14 Modified butt joints



Practical structural design

The examples shown in Fig. 3.15 highlight correct and incorrect methods of designing or assembling a variety of bonded structures. The key in every case is to load the joint with a combination of compression and shear forces and to avoid destructive peel and cleavage loads.

Fig. 3.15 Examples of good and bad designs



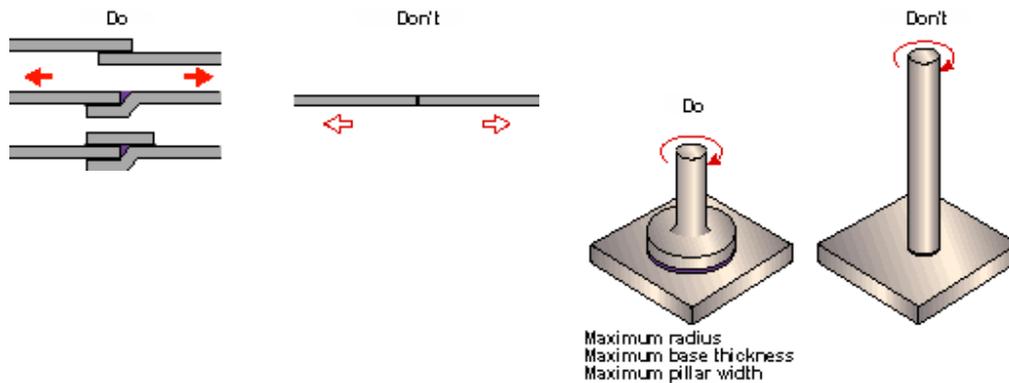
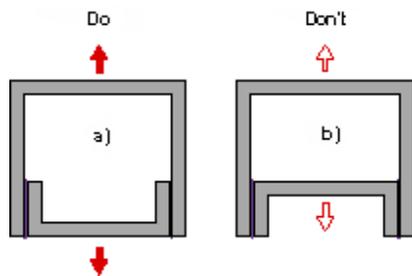


Fig. 3.16 Box structure designs



The box structure shown in Fig.3.16b is based on welding practice, allowing easy access for welding tools - although the design does not favour adhesive bonding. By reversing the closing panel (Fig. 3.16a) the left-hand box is 3-4 times stronger than that on the right.

Hybrid joints

Hybrid joints are those which combine two or more joining methods. For example, adhesive bonds with either screws or rivets may be produced, and sheet metals can be successfully welded through a layer of suitable adhesive. Epoxy or elastosol adhesives are often used in such hybrid joints, either weld-bonded or riv-bonded (rivet and adhesive) in automotive manufacture.

Screws, rivets or welding are useful in holding components together while the adhesive cures, obviating the need for additional temporary support and, where peel or cleavage forces cannot be avoided, they can be used to counteract such loads. Although the adhesive may well be secondary, it will still make a significant contribution to the overall stiffness of the structure.

Three distinct classes of hybrid joint are worthy of note:

- high strength
 - adhesive and mechanical or welded joint work together, reaching very high levels of strength
- jiggling
 - strength of adhesive determines strength of hybrid joint; mechanical or welded joint is used mainly for jiggling the parts while adhesive cures

- sealing
 - strength of mechanical or welded joint determines strength of hybrid joint; adhesive is mainly used for sealing and damping

Ease of assembly & joint design

Joint design must allow cost-effective assembly. It is usually better to design joints so that the parts are pressed down on the adhesive rather than slid into position. *Placement on* rather than *sliding over* ensures that the adhesive is not pushed out of the joint detail. However, placement can result in trapped air, and appropriate precautions must be taken.

The design must also allow the adhesive to be positioned in an appropriate pattern. Stripes and crosses are better than closed-loop patterns because they help avoid air entrapment when the components are brought together.

Large bonded areas require careful and even dispensing of adhesive otherwise considerable pressure is required to squeeze out and spread the adhesive to a uniform thickness.

Case history: *Use of adhesively bonded patches for in-situ pipeline repair*

As a result of in-service external corrosion, a steel water pipeline was suffering from loss of wall thickness, with leaks in some areas. A cost-effective repair method was required, as the water company did not wish to replace the pipeline.

Available options

- Cut out grossly corroded sections, replace with patches or new pipe lengths and repair by welding on site - expensive, long downtime
- Use adhesive bonding to repair cavities and holes in the pipeline

What was done

Two adhesive bonding procedures were required: fill cavities and restore external surface; repair holes up to 5mm diameter.

Cavities -

Procedure adopted was: degrease damaged surfaces using a trichloroethene product and abrade. Fill with mastic compound such as Araldite 64257 and hardener HY 850, plus silica filler. A similar approach was used to rebuild the external coating, except that the epoxy was reinforced with layers of glass fibre chopped strand mat.

Holes -

Corroded area and a steel patch (200 x 200 x 2mm) were cleaned and degreased. Priming and anti-corrosion treatment were applied and the patch bonded in place using epoxy adhesive. Patches were held in position by a series of metal straps until cure was complete.

Benefits

Satisfactory pipeline performance was obtained by use of the above adhesive repair methods. Complete replacement of the pipeline was avoided.

Implications

Provided resistance to humidity is achieved, the use of adhesive repairs is attractive for this type of application.

4. Surface Pre-treatment

Synthetic adhesives have been used successfully for many years in diverse sectors of industry including aerospace, automotive, biomedical/dental, construction, electronic, marine, sport & leisure.

Although in a few applications no surface pre-treatment is necessary (the automotive industry has been using specially designed adhesives for bonding oily metal adherends since the 1950s), it is accepted that to obtain the optimum performance from an adhesive joint a pre-treatment is required. The type of pre-treatment is often a compromise between the best surface preparation, economics of component manufacture and health and safety issues.

If the economic and engineering advantages of adhesives are to be realised, the adherends must be given a suitable surface pre-treatment. The benefits of using appropriate surface pre-treatments are:

- enhanced mechanical performance of joint
- improved joint durability in aggressive environments
- increased service-life of component
- ability to bond difficult adherends, e.g. polyolefins and polytetrafluoroethylene

Purpose of pre-treatment

Pre-treatment is carried out to achieve one or more of the following:

- To remove completely, or to prevent formation of, what are often referred to as weak boundary layers. A useful analogy to describe this concept is applying a pressure sensitive tape (e.g. Sellotape) to an adherend coated with a powder (e.g. talc). The Sellotape will simply adhere to and pull off the talc from the adherend. No bond will form between the tape and adherend. Examples of weak boundary layers include weak oxide scale on metallic substrates, plasticisers which have migrated to the surface of polymers, mould release agents from processing of composites. Other surface contaminants are dust, dirt, grease, oils and even finger marks!
- It is well established that to form an effective bond, intimate molecular contact between adhesive and adherend is required. The correct surface pre-treatment will optimise this degree of contact, which may be brought about by chemical modification of the adherend surface.
- To protect the adherend surfaces before bonding. This is often necessary, particularly with metals which after surface pre-treatment have a surface that is

highly reactive not only towards adhesives but also to atmospheric contaminants. To preserve the integrity of the adherend surface it is usually necessary to bond the surface within a few hours of treatment, or to coat it with a primer which is compatible with the adhesive to be applied later. A primed surface can protect the adherends for up to several months.

- To produce a specific adherend surface topography, thereby altering the surface profile, and possibly increasing the bondable surface area, that is, to roughen the surface.

Main types of pre-treatment

There is a wide range of surface treatments available. Many adhesives or adherend suppliers give advice. Best practice is collected in Standards; ISO 4588 (for metals) and ISO 13895 (for plastics) are currently under revision. Techniques can be classified into five groups, according to the nature of treatment:

Cleaning/Degreasing: Removal of loose solids can be accomplished with a clean brush or blast of clean, dry air. Organic solvent or alkaline aqueous solution removes organic materials such as grease, oil and wax from adherend surfaces. This can be accomplished by wiping, dipping or spraying.

Surface Roughening: Techniques where abrasive materials are employed to remove unwanted layers and generate a roughened surface texture.

Chemical Treatments: Immersion of the adherend in an active solution which has the power to etch or dissolve a part of the adherend surface or change it in such a way that the treated surface becomes chemically active. An electrochemical reaction can also be included where current is transferred through an electrolyte between an auxiliary electrode and the adherend surface, e.g. anodising, and this introduces several additional factors to be controlled.

Physical Treatments: Techniques where the adherend surface is cleaned and chemically modified by exposure to excited charges or species. Techniques such as corona discharge, plasma, flame or exposure to ultraviolet/ozone are examples in this group.

Primers: Alternative surface treatments, often simpler than chemical or physical methods, applied by dipping, brush or spray. They can chemically alter the surface (e.g. silane coupling agents, chromate conversion coatings), or protect the preferred surface already generated by another method (e.g. aerospace primers after anodising).

In general, the above types of surface pre-treatment can be divided into three major categories: mechanical; chemical; energetic. Each of these can be further subdivided into a given technique or method of surface preparation, as illustrated in Table 4.1.

Overview of mechanical, chemical & energetic pre-treatment

Table 4.1 Surface pre-treatments for adherends

Mechanical	Chemical	Energetic
Alumina gritblast	Solvent cleaning	Plasma
Cryoblast	Detergent wash	Corona discharge
Sodablast	Acid etch	Flame
Peel ply	Anodising	Excimer laser
Silicon carbide abrasion	Primer	

Selection of a pre-treatment should be based on issues such as cost, production, durability and health and safety. Pre-treatment facilities can include equipment, chemicals and consumables. Key surface features which should be kept in mind are wettability, roughness, soundness, stability, contamination, uniformity and adhesive compatibility.

Surface pretreatment must always be appropriate to performance requirements, and be compatible with manufacturing procedures and costs. Use of aluminium in four industries illustrates this:

- Aerospace (wing skin to honeycomb)
- complex and high cost; etch, anodise and prime sequence before lay-up with epoxy adhesive
- Automotive (bodyshell)
- metal supplier provides material with conversion coating and press lubricant applied, before application of epoxy paste adhesive by manufacturer
- Rail (carriage panels to frame)
- solvent clean, then primer or coupling agent applied to localised areas in factory, before application of polyurethane adhesive
- Automotive (engine-block flanges)
- alkali cleaning before application of anaerobic acrylic, or silicone sealant in factory

Mechanical pre-treatment

Mechanical abrasion is the most widely applicable surface preparation technique, being suitable for most materials.

Mechanical abrasion will remove weak boundary layers. It will also change the surface topography of the adherend, increasing the bondable surface area on a microscale. Furthermore, mechanical abrasion will enhance the adhesive's ability to 'wet' (when the adhesive readily and completely covers) the surface of the adherend.

The simplest form of abrasion uses silicon carbide paper to abrade/polish surfaces. This method may be carried out dry or in conjunction with a suitable solvent. The quality of the adherend surface obtained with silicon carbide depends upon the grit size and whether the operation is performed manually or mechanically. It is necessary to monitor carefully the abrasion since, if the process is carried out for too long, surface debris initially removed can be re-deposited. For composites, it is important to note that mechanical abrasion may cause fibre damage and impair performance of the joint.

Blasting is another form of mechanical abrasion and includes alumina grit blasting, shot blasting, cryoblast and sodablast. Shot blasting is only appropriate for treating ferrous surfaces. For other metals, grit such as alumina should be used. Cryoblast and sodablast are used for preparing composite adherends. Cryoblasting is less aggressive than alumina grit and consists of solid carbon dioxide pellets.

Sodablasting was initially used in the aerospace industry as a preparative method for painting aircraft. It uses a suspension of sodium bicarbonate in water. A disadvantage of sodablast is that it increases the water content of composite and hence brings a need to dry the component before bonding. The variables associated with blasting are the chosen particle, the particle size, pressure of blast, exposure time, angle of blast and distance between blast nozzle and adherend.

In the peel ply surface preparation method used for composites before curing, a fabric material is used to cover the external surface of the composite. During the cure cycle, part of the matrix will flow and penetrate the fabric and eventually, after curing, becomes part of the laminate. When the laminate is required for bonding, the fabric is peeled off, fracturing the resin between the fabric and the first layer of reinforcement, producing a clean, roughened surface to which the adhesive can be applied. The surface morphology obtained is dependent on the nature of fabric and type of weave used.

Chemical pre-treatment

There are several different chemical methods by which adherends can be cleaned and prepared for bonding including: solvent cleaning, detergent wash, acid etch, anodising and primers.

Adherends are frequently contaminated with oils or grease. An effective method of cleaning ceramics, glass and metal adherends is by an organic solvent vapour degrease. Solvent is boiled in a chamber whereupon it condenses on the cooler adherend, and dissolves the oil and grease before it drips back into the heating tank. Very clean surfaces can be obtained in this way. Consideration must be given to local or national environmental regulations on the use of organic solvents.

Alternatively, if small enough, the adherend can be immersed in an ultrasonic bath containing a solvent. Agitation of the adherend increases the speed of treatment.

Solvent cleaning in its simplest form can be performed by using a suitable cloth to apply the solvent to the adherend. The cloth should be applied so that the surface is wiped in one direction only, to prevent any surface debris from being re-deposited. The cloth should also be replaced regularly.

Solvent cleaning is often applied to polymeric materials, but the correct solvent must be chosen with care since solvents are organic based and may attack, be absorbed by, or plasticise the adherend. Plastics material suppliers can usually advise.

Detergents dissolved in water, alkaline or acidic solutions and used at temperatures of about 50-70°C may also be used to supplement or replace the organic solvent cleaning process.

Metal adherend surfaces are rarely of pure metal, but are a combination of oxides, sulphides, chlorides and other atmospheric contaminants. This results in a surface which is mechanically weak and is prone to crack and flake off.

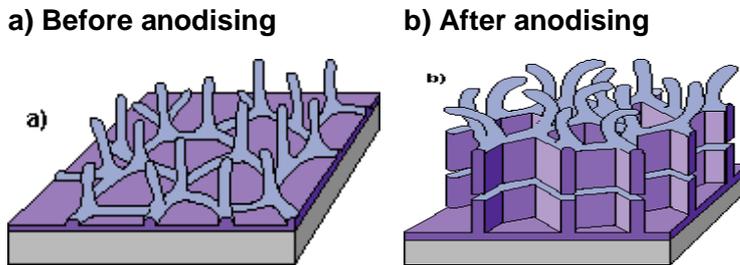
Acid etching is a well established method of removing weak metallic scale, in favour of forming an oxide layer which is mechanically and chemically compatible with the adhesive. Hence, different acid treatments are applied to different metal adherends, for example, chromic acid for aluminium, sulphuric acid for stainless steel and nitric acid for copper. Some metals require an alkaline, rather than an acid, pretreatment, such as alkaline peroxide used for titanium.

Acid pre-treatment can also be applied to certain plastics. Chromic acid is used to surface treat polyolefins. Even PTFE, known as a non-stick material, can be bonded when treated with a solution of sodium naphthalenide in tetrahydrofuran.

Anodising has been exploited extensively by the aerospace industry as a surface pre-treatment for aluminium and titanium alloys. Anodising is performed only after the adherend has been etched. The purpose of anodising is to deposit on the adherend a porous and stable oxide layer on top of the oxide layer formed after etching. The porous oxide layer enables adhesive (or primer) to penetrate the pores readily to form a strong bond and is resistant to environment attack by H₂O.

Anodising is a type of electrolysis where the adherend is the anode, and a typical electrolyte is phosphoric acid. An inert electrode is used for the cathode. The differences in the structures of aluminium oxide layers before and after anodising are illustrated in Fig. 1. A disadvantage of anodising is that it is a time-consuming operation. In addition, there are a number of variables which must be carefully controlled: applied voltage, time of anodising, temperature and concentration of electrolyte.

Fig. 4.1 Oxide layer on aluminium:



Application of a primer to an adherend is another form of surface pre-treatment mainly used for materials such as metals and ceramics. Generally, the primer is the final stage of a multistage pre-treatment process. The primer acts as a medium which can bond readily to the adherend and adhesive.

Some adhesives have high viscosities and thus do not flow readily over the adherend, or the adherends have 'difficult to bond' surfaces (e.g. copper). The primer, which is formulated so that it represents a solvated version of the adhesive, readily wets the adherend. The primer is then cured on the adherend as desired. The adhesive, when applied to the primed surface, being chemically compatible, will establish a strong joint on curing.

Primers often contain ingredients which enhance the environmental resistance and thermal stability of the joint, as well as protecting the adherend from hydration and corrosion. The cured primer can protect the adherend for several months before bonding.

Energetic pre-treatment

Energetic surface pre-treatments which have been reported in the literature include flame, corona discharge and plasma (FCDP) and excimer laser. All of these procedures cause a change in the surface texture of the adherend, brought about by the interaction of highly energetic species with the adherend surface. These pre-treatment methods have been applied to metals and in particular composites and plastics.

A plasma is an excited gas consisting of atoms, molecules, electrons, ions and free radicals. A plasma is generated by applying a high frequency and high voltage between, for example, parallel plate electrodes in a low pressure chamber. The advantage of this method is that it allows treatment of adherends by different plasmas of argon, ammonia, oxygen or nitrogen.

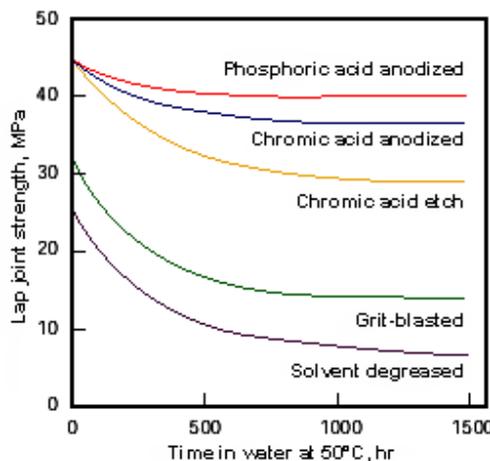
Plasmas created from inert gases are generally used to clean the surfaces of adherends. The excited species generated can have one or more of the following effects on the adherend:

- surface clean
 - the excited species may have sufficient energy to displace some surface contaminants

- degradation and ablation
 - the plasma can cause degradation of the surface of polymeric materials and lead to removal of debris from the surface
- crosslinking
 - the surface of the adherend may become crosslinked and prevent the formation of weak boundary layers
- oxidation
 - the plasma can lead to introduction of oxygen-containing groups, for example carbonyl, brought about by oxidation of the polymer surface; this can lead to the adherend being readily wetted by the adhesive

If instead, a plasma is created in air at atmospheric pressure, the air when ionised appears as a blue/purple glow with faint sparking, and is termed a corona. The effects which the corona discharge can have on the adherend surface are similar to those described above. Corona treatments are usually applied for preparing thin polymer films and composite laminates.

The effect of a flame treatment is to oxidise the adherend, which produces polar groups such as $-\text{COOH}$, $-\text{C}=\text{O}$, $-\text{OH}$, $-\text{NO}_2$, $-\text{NO}_3$ and $-\text{NH}_2$. This creates a surface better suited to wetting by the adhesive. This method of surface pre-treatment has been applied successfully to carbon/PEEK and glass/polypropylene composites.



The variables of flame treatment include type of gas, gas/air (oxygen) ratio, the rate of flow of mixture, exposure, time and distance between flame and adherend.

Fig. 4.2 Effects of surface pretreatment on the durability of aluminium alloy/toughened epoxy joints subjected to accelerated ageing in water at 50°C

Figure 4.2 illustrates the effect that some of the surface pre-treatments described have on lap shear strengths of aluminium/epoxy joints.

Clearly, the best performance is obtained from bonded joints having been prepared by an etchant and post-anodised. In contrast, a simple solvent degrease or gritblast in this type of environment is inadequate.

Specific methods for pre-treatment

Substrate surface pre-treatment is necessary in order to:

- remove chemically incompatible layers
- overcome any low surface energy effects which inhibit bonding
- achieve a surface topography which is receptive to the adhesive
- ensure good durability of the bonded joint

Standard method for simple surface preparation

Simple surface preparation techniques such as cleaning and degreasing are required for most adhesives. Certain adhesives, for example cyanoacrylates, may be used alone on plastics materials as they can penetrate or dissolve away surface debris.

Cleaning and degreasing

- use non-ionic detergents, alkaline cleaners or isopropyl alcohol (IPA)
- do not wipe with fibrous cloths or tissues
- allow to dry

Surface preparation method - SPM

The following method is suitable for most materials. A silane coupling agent may be used to indicate surface wettability and increase the bonded joint's long-term durability.

- Remove oil or grease contamination
- Abrade or shot blast using medium grit (120 - 200 mesh suitable). Grit should preferably be alumina (bauxite). Do not use steel or iron shot of any description on aluminium alloys
- Remove coarse debris (if present) with water jet
- Remove fine debris with solvent impregnated wipes
- Ensure surface is completely dry
- Bond or prime immediately

5. Quality Assurance

Adhesive bonding of composites is used in a wide variety of industries: from consumer goods packaging, through to aerospace.

While there is a large number of non-destructive testing (NDT) techniques that may be used to detect the variety of defects that might be found within a bonded structure, due to the enormous scope covered by the term 'adhesively bonded joint' and the variety of defects that may be found within a joint, no single technique can be specified as the industry standard.

It is also recognised that inspection of a bonded joint using one, or even two of the techniques available cannot guarantee detection of every defect within the bond-line. However, when used as part of a systematically managed and controlled operation - from design of the joint, through to final assembly - it can reduce the possibility of poor joints being produced.

Defect types

Types of defect typically found in an adhesive joint are shown in Fig.5.1

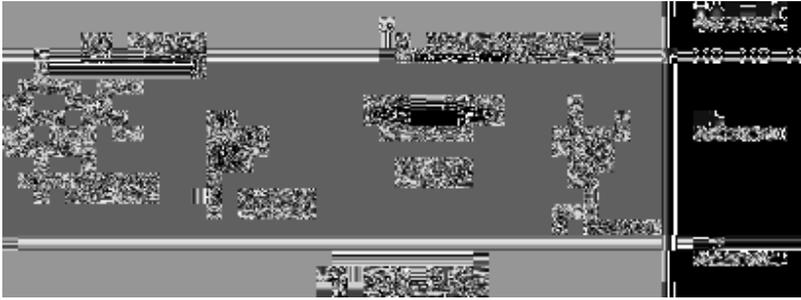


Fig.5.1. Typical defects within adhesively bonded joints

- A: Disbonds occur as a result of failure of the interface between the adhesive and the adherend, or the surface treatment (e.g. primers) applied to the adherend. In the case of a zero-volume disbond (B in Fig.1) the two surfaces are in intimate contact but no mechanical or chemical bonding exists at the interface, which means that they are particularly difficult to detect using NDT methods.
- B: Zero-volume disbond is also called weak bond or kissing bond. The interface is bonded but bond strength is not assured.
- C: Poor cure results in poor cohesive strength. It can arise from incomplete mixing of the adhesive, inadequate control of temperature, light or other forms of energy to activate the cure, or pressure variations during the cure cycle.
- D & E: Porosity and voids are due to volatile substances within the adhesive (such as water vapour), entrapped air or insufficient application of adhesive.
- F: Cracking within the adhesive may happen as a result of incorrect cure, brittleness of the resin after cure, or it may be due to filler loading in the adhesive formulation. High strength adhesives and those without toughening agents tend to be brittle and are, therefore, susceptible to cracking when shock loaded or exposed to temperature cycling.
- G: Delamination within the adherend, while not actually a failure of the bonded joint itself, should be noted as it may obscure other damage within the joint when using certain NDT techniques. This type of failure may also occur in cases where the interfacial strength at the adhesive/adherend regions is stronger than the fibre/matrix interface in the composite adherend.

NDT techniques

Some common techniques used for the NDT of composite joints are briefly described below.

Manual methods such as the 'coin-tap' rely on the fact that when bonded composites are tapped, areas containing delaminations or disbonds produce a duller sound than good areas. This technique is used as a quick and easy method to get a feel for bond integrity.

Ultrasonics techniques, of which there are many variants, are the most commonly used method for inspection of adhesively bonded joints. Ultrasonic waves are propagated through the structure and the amount of energy transmitted or reflected depends on the properties of the materials and any defects within the structure.

One of the limitations of ultrasonics is that some composite materials are highly attenuative of ultrasound and therefore the thickness of material that can be inspected may be limited. Most of these techniques also require a coupling agent such as water or a gel between the part to be inspected and the transducer.

Low frequency vibration techniques are less sensitive than ultrasound but are still recognised as an effective way of detecting disbonds in bonded joints. Shearographic/Holographic inspection uses interference of laser light to create three-dimensional images of the joint before and while being stressed. Comparison of these two images can be used to detect the presence of sub-surface defects. The most common use of this technique is to detect disbonds in adhesively bonded honeycomb panels.

Radiography is of limited use in the inspection of adhesively bonded composite joints. X-ray adsorption of composite materials is very low and disbonds are generally oriented in a plane perpendicular to the X-ray beam, which makes them difficult to detect. Since damage is generally well contained within the joint, it is not easy to introduce X-ray opaque penetrant into defects. The use of X-ray opaque adhesives is a possibility.

Thermography techniques can be passive or active. In passive thermography, an external heat source is applied and the surface temperature monitored either on the same side as the heat source to detect surface defects, or on the opposite side to the heat source to detect defects deeper within the material. Active thermography involves subjecting the joint to a cyclic stress or resonant vibration. This is particularly good at detecting disbonds between skin and honeycomb, as the disbonded area resonates, generates heat and is detected.

Dielectric measurement may be performed when electrically conductive composites are being joined. An electromagnetic wave can be generated in the dielectric (adhesive) layer that travels along the length of the bonded joint and back to the start point. Differences in the initial and returning wave can be used to investigate the state of cure of the adhesive, locate voids and find areas of poor interface between the adhesive and adherend.

Other NDT techniques for adhesive joints are summarised below. These are less used than the conventional methods described above, however, each technique can provide satisfactory results if used in the correct way for the specific item under test.

Beta-ray Backscatter

Beta rays (stream of electrons) are directed at the specimen's surface layer. A detector measures the rate and intensity of electron backscatter. Gamma rays or X-rays can also be used for this type of testing. This technique is often used to measure paint thickness and examine plastic coatings and composite laminates.

Radioactive tracer

A low activity, radioactive tracer is injected into certain materials or equipment. The tracer's presence and migration are then monitored by radiographic film, probes or ionising counters. This technique is used to monitor wear, corrosion, and crack propagation.

Electrochemical impedance spectroscopy (EIS)

The impedance spectra change shape depending on the type of flaw detected in the specimen. It can be used to detect corrosion, flaws and the presence of moisture in an adhesive bond.

Detection of kissing (weak) bond

Assurance of bond integrity is particularly important for critical components/structures and there is a considerable amount of ongoing research into the reliable detection of defects by non-destructive methods.

Whilst normal disbonds can be detected easily using the technologies outlined above, weak bonds and zero-volume disbonds have proved extremely elusive. This is partially because it is difficult to simulate a kissing bond defect specimen. A commercial product called ElectRelease® that can be 'unzipped' by applying an electric field can possibly be used. So far, several applications of ultrasonic methods are short listed for further evaluation and optimisation. These are: nonlinear harmonic generation, swept-frequency ultrasonic spectroscopy, oblique incidence ultrasound, shear-wave resonance, and guided waves. These techniques are briefly explained below.

Ultrasonic Spectroscopy

Swept-frequency ultrasonic spectroscopy, using a long toneburst 'chirp' involves the capture of multiple superimposed reflections through the structure and determining the frequency content. The ratio of the amplitude of the two peaks (a good part and a defective part) can be used to detect and measure changes in ultrasonic properties across the joint, with the potential to assess the relative strength of the bond.

Harmonic Imaging (Nonlinear Ultrasonics)

It is assumed that the kissing bond contact interface is 'nonlinear'. Such nonlinear coupling would be expected to convert incident ultrasonic energy into harmonics of the excitation frequency. This harmonic generation is detected and analysed.

Oblique Incidence Ultrasound

Though it is difficult to implement the oblique-incidence method, it is expected to be more sensitive to interfacial properties, which may help in the examination of kissing bonds.

Shear-wave Resonance

The presence of adhesive causes the shear-wave resonance to change in frequency, as well as being damped. The level of damping and shift in resonant frequency could possibly be used to determine the modulus of the adhesive layer.

Guided waves

It is already known that guided waves can detect a significant change in the stiffness of the interface, however, it is still unclear how to determine the level of weak bonds or kissing bonds.

Further information:

Adhesive bonding - guide to best practice. Section 5:Quality assurance, plus durability of bonded joints

6. Health and safety

Adhesives occupy a significant place in industry and used correctly are universally beneficial. This part of the Best Practice Guide reviews hazards and discusses safe use of adhesives. The importance of health and safety stems from law and, of course, the worker's entitlement to safety.

The following paragraphs describe legal requirements applicable to the UK

Health and safety at work act 1974 (HSWA)

In the UK, the Health and Safety at Work Act 1974 (HSWA) introduced an all-embracing legislation applicable to everyone at work. The act imposed a general duty on the employer - which may be an adhesive manufacturer, supplier or user - to ensure the safety of its employees. The main points are:

- provision and maintenance of plant and systems of work which are safe and without risks to health
- safe use, handling, storage and transport of articles and substances
- provision of information, instruction, training and supervision
- condition of the workplace and ways in and out of the premises
- working environment (this could include heating, lighting, ventilation, noise control)

The act also imposes a duty of preventing risks to non-employees, a duty on manufacturers and suppliers in respect of the safety of substances and articles used at work, and a duty of employees to take reasonable care for their own health and safety and that of others.

It's worth noting that health and safety datasheets should be provided free of charge by adhesives suppliers.

Control of substances hazardous to health regulations 1999 (COSHH)

Adhesives are substances which have hazards associated with their use. The COSHH regulations concern control of exposure to a hazardous substance, whether it be a chemical or an adhesive, which may be harmful to health in work situations.

A substance hazardous to health is any substance described as toxic, very toxic, harmful, corrosive or irritant, any substance with a prescribed exposure limit, a dust of any kind present in substantial quantities in air, or any other substance of comparable hazard.

In each case, the employer must recognise and appreciate hazards related to a particular substance and minimise risks of its use. Action required falls into six basic sections -

Assessment of health risks in all work activities

Employees are not permitted to carry out work activities involving any hazardous substance unless a suitable and sufficient assessment of health risks has been made and appropriate action taken.

Control

Exposure of workers to hazardous substances must either be prevented or controlled. Control measures, such as local exhaust ventilation, must be properly used, maintained and tested.

Monitoring of exposure levels

Atmospheric sampling may be required in some situations, particularly where substances involved have an occupational exposure limit.

Health Surveillance

This may be required for certain workers, for example where carcinogens or sensitises are involved. Appropriate health surveillance for substances known to cause sensitisation would include enquiries seeking evidence of symptoms. However, in some instances the only health surveillance required is the collection and maintenance of health records.

Instructions, training and information

Details of health risks and precautions to be taken must be given to those workers who may be exposed.

Monitoring of industry for compliance with health and safety legislation is the responsibility of the Health and Safety Executive (HSE) in the UK. Regularly updated records for inspection by an HSE inspector are a key part of COSHH.

Personal protective equipment

The production and marketing of personal protective equipment (PPE) such as respirators, dust masks, safety glasses, footwear and clothing, is subject to an EC Directive. PPE products must be certified by an approved body, bear the CE mark and be supplied free of charge to the employee if they are required for his/her work activities.

Hazards and risks

What is a hazard?

The hazard of a chemical or substance is its potential to cause injury to a person or damage to the surroundings. It is an intrinsic property.

What is a risk?

A risk is the likelihood that the hazard will be allowed to cause injury or damage. The extent of the risk is the magnitude of the consequences, and the number of people who might be exposed.

Hazards associated with adhesives

There are four main types of hazard:

- physicochemical
- toxicological
- environmental
- miscellaneous

Physicochemical hazards

Explosive: no adhesive is considered explosive! However, certain adhesives may emit vapours which can form explosive mixtures with air.

Oxidising: these are agents which spontaneously give off oxygen either at room temperature or under slight heating. They can react vigorously with flammable substances, and thus can cause fires.

Flammability: some adhesives have the ability to ignite and burn readily. Fires pose the risk of burns, asphyxiation (depriving the body of sufficient oxygen) and inhalation of hazardous decomposition products. Flammable adhesives have three main characteristics:

- flash-point
- auto-ignition temperature
- explosive limits

Flash-point: the minimum temperature at which vapours from a liquid adhesive ignite in air when an ignition source has been provided. The lower the flash-point, the more flammable the adhesive: for example, a toluene-based adhesive has a flash-point of 4°C.

Auto-ignition temperature (AIT): the temperature to which an adhesive has to be heated to cause self-sustained combustion. It occurs in the absence of a spark or flame. The AIT is invariably higher than the flash-point temperature: for example, a toluene-based adhesive has a AIT of 536°C.

Explosive limits: the concentration range of a flammable vapour (% by volume in air) evolved from an adhesive in which explosion can occur on ignition in a confined area. For any given flammable adhesive there is a lower explosive limit (LEL): for example, a toluene-based adhesive has a LEL of 1.27% and upper explosive limit (UEL) of 7%.

Table 6.1 shows the hazards associated with adhesives.

Table 6.1 Overview of hazards caused by adhesives

	Causes Burns	Flammability	Explosion	Harmful Vapours	Harmful to skin/eyes	Comment
Epoxides				(*)	.	Some hardeners can cause respiratory

						sensitisation and asthma.
Polyesters		•			•	Some polyesters cause eye irritation and tissue damage.
Formaldehyde resins	•			•	•	Toxic: Causes burns.
Polyurethanes				•	•	Potential respiratory sensitisation and occupational asthma.
Acrylics		•		•	•	Flammable, odour problems.
Cyanoacrylates				•	•	Causes rapid bonding of skin and eyes. Odour irritation.
Anaerobics				•	•	Low acute toxicity. Some are skin sensitising agents. Slight odours.
Polysulphides		•				Oxidising characteristics of cure system may present a fire hazard.
Silicones					•	Low overall toxicity. Mild skin and eye irritation.
Solvent-borne		•	•	•	•	Prolonged inhalation can cause anaemia, liver and kidney damage.
Water-borne				(•)	•	Relatively safe products, can

						be a skin irritant (dermatitis).
Hot-melts	•			(•)		Risk of burns from the hot adhesive, 120°C up to 240°C.
Powder Forms			•		•	Dusts can be respiratory irritants.
Plastisols, curing rubbers	•			•		Inhalation of VOCs.
UV Curing				•	•	Exposure to UV harmful (depending on wavelengths used). Inhalation of ozone, (UV curing equipment) can cause health problems.
<p>Note: Table 6.1 is only a general overview and is not intended to be comprehensive. Users of adhesives must follow health & safety information provided by manufacturers. If in doubt, always contact the adhesive manufacturer for advice.</p>						

Toxicological hazards

Toxicology is the study of the detrimental effects of substances on living systems. Toxicity is the relative degree of being poisonous. It is an intrinsic property. Toxicological hazards can be termed as the following:

- toxic
- harmful
- irritant
- sensitising
- corrosive/causes burns

Four primary routes provide access to the body:

- ingestion (by eating or drinking): the substance enters the stomach and is absorbed as 'food'
- inhalation (by breathing the chemical in as a vapour or mist): the substance enters the lungs and is absorbed like oxygen
- penetration or absorption (through the skin): the substance enters human tissue and bloodstream

- damage to the outer surface of the skin or the eyes

The physical state of an adhesive influences its route of entry. Aerosols and vapours from solvent-based adhesives may cause inhalation effects and are the most difficult to control. Liquid adhesives may cause penetration and possibly ingestion effects.

Toxic: toxic effects are generally quoted in terms of lethal doses to animals. The term *LD50* or *Lethal Dose 50* is the dose which when given to test animals, kills half (50%) of them. The lower the LD50, the more toxic the adhesive. The LD50 is often found on safety data sheets.

Harmful: a harmful substance may cause death or acute or chronic damage to health if allowed access to the body. Harmful effects can be split into two categories:

- acute: observable immediately after exposure; has a short duration
- chronic: observable after a long time-interval; has a lengthy duration

Organ-specific toxicity

These substances can damage various organs of the body, for example, solvent-based adhesives can affect liver-function.

Geno-toxic effects

Carcinogenicity: ability to cause cancer.

Mutagenicity: ability to induce heritable genetic defects.

Toxic to reproduction: ability to impair the reproductive function and/or produce non-heritable damage to embryos.

Irritant: irritation manifests itself as inflammation of tissue. The tissue may be skin, eyes or the respiratory systems.

Skin contact with adhesives may cause irritant dermatitis. Symptoms include red, itchy or blistered skin.

Sensitising: sensitisation causes the exposed body to become sensitised or develop an allergy. Sensitisation may occur on first contact or after several contacts. The time-lapse is referred to as the *induction period*. Once sensitised, the body will experience an adverse reaction, possibly on contact with a minute quantity of the sensitising agent.

Skin sensitisation, also referred to as *allergic contact dermatitis* manifests as a rash, but develops into an allergy.

Respiratory sensitisation manifests itself as occupational asthma.

Corrosive/causes burns: some preparations destroy living tissue and these are classified as corrosive.

Miscellaneous

These hazards do not fit into the physicochemical, toxicological or environmental categories. Examples include the rapid skin bonding characteristic of cyanoacrylate

adhesives, and the use of temperature and pressure sensitive adhesives at extreme conditions.

Exposure limits

In the UK, many substances are subject to statutory exposure limits, relating to inhalation. These are published annually in EH 40/00, along with the current lists of substances known or suspected to be carcinogens.

An exposure limit designated MEL requires the employer to reduce exposure to that substance to the lowest level reasonably practicable and under no circumstances must the MEL be exceeded. An exposure limit designated OES indicates an acceptable maximum exposure. These figures will be quoted on manufacturers' safety data sheets, where applicable.

Environmental

The environment can be split into three areas:

- air (atmosphere)
- water (rivers, lakes, seas)
- soil

An environmental hazard has the potential to cause harm to humans or other life-forms via the environment. For adhesives, these concerns arise from disposal of waste adhesive and release of vapours from certain solvents.

Control of VOC emissions

Adhesive users must face the challenge of meeting standards for VOCs emission in the UK. Adhesive coaters using more than 5 tonnes per year of solvents at a location are now subject to local authority air pollution control. Operators must reduce VOC emissions to 50mg (as carbon) per cubic metre of vented air by June 1998.

Control measures are encouraging the use of water-borne or hot-melt systems. However, these systems require specialist application equipment and extended drying times, and they can suffer from limited tack and variable bonding performance. This equates to an increase in cost.

Waste management

In the UK, a new *duty of care* came into force on 1 April 1992 to control the disposal of factory waste. Dangerous substances classified as special waste are subject to additional regulations and high disposal costs.

Adhesive users must aim to restrict the amount of waste generated, ensure containers are completely empty and, before disposal, evaporate or incinerate residual contents.

Recycling

Recovery of adhesives is usually not cost-effective, however, tailoring adhesives to ease recycling of bonded materials is a feasible issue and is receiving attention by the paper and board packaging industry.

Environmental auditing and ecolabelling

An environmental audit of the manufacturing process helps demonstrate to customers that a company is complying with legislation. The audit considers raw materials, energy usage, materials processing, emission of pollutants and generation of waste. BS EN 14001: Environmental Management Systems provides a structure for this activity.

The EC ecolabelling scheme, which uses a flower logo, aims to identify goods that caused least damage to the environment during their manufacture.

Energy

Adhesive bonding is a relatively low user of energy, although energy consumed to produce the adhesive itself, and oven curing in production, must be taken into account.

Renewable resources

Products based on natural, renewable resources are not without environmental impact. Adhesives produced by biotechnology is a current topic of adhesive research and development.

Labelling and symbols



Fig. 6.3 Seven main symbols for hazardous substances

The 2000 Chemicals (Hazard Information and Packaging for Supply) Regulations (CHIP) require suppliers to determine whether or not a substance is dangerous and classify it. Any packaging in which the substance is supplied must be labelled.

Figure 6.3 shows the seven main symbols for hazardous substances.

Safe use of adhesives

There are two main guidelines for using adhesives safely:

- use the least hazardous adhesive available for the application
- minimise human and environmental exposure

Safe use may be achieved by:

- defining a safe system of use
- implementing the system
- monitoring the system

Safe storage

- keep adhesive containers tightly closed when not in use. This prevents the escape of volatiles into the air. Tightly sealed containers preserve shelf life and quality of the adhesive.
- store adhesives in a well ventilated area. A temperature range of 5 - 30°C is normally recommended on safety datasheets accompanying the adhesive.
- only minimum quantities should be stored for immediate usage. Containers must be correctly labelled. Chemically-resistant containers must be used.
- do not store adhesives with reactive or flammable chemicals. This poses a spillage and fire hazard.

Safe application techniques

Avoid inhalation hazards by using adequate ventilation methods such as extraction fans and opened windows. When required, use personal protective equipment (PPE) such as respiratory equipment, gloves, goggles or a dust mask.

Adhesive dispensing

Use appropriate adhesive dispensing equipment. This will avoid the risk of skin and eye contact. Barrier cream or impermeable gloves may be used. Safety glasses should be worn.

Safe disposal

In case of spillage -

- shut off source of spillage
- identify adhesive and its hazards
- prevent adhesive from spreading or entering drains by surrounding it with a non-combustible, inert material such as sand or earth
- absorb spillage and transfer into a sealable container
- package and dispose of safely

Empty containers should also be disposed of safely and separately from general workplace waste. Use approved disposal agencies.

Note: Actual method of disposal depends on the type and quantity of adhesive.

- incineration - must take place in correctly designed equipment by an authorised contractor
- landfill in an approved site

In case of fire:

- water is NOT suitable for flammable adhesives
- use appropriate fire extinguisher for the fire concerned
- remove remaining containers of flammable liquids and water-spray to keep cool; place in a safe area away from the fire zone

7. Glossary of terms used in adhesive bonding

It is always useful to document the accepted meaning of terms used in a specialist subject, for the benefit of both novice and established expert. Commonly used terms are explained below, mostly reproduced from the draft European standard prEN 923.

Adherend	A body that is, or is intended to be, held to another body by an adhesive.
Adhesion	The state in which two surfaces are held together by surface bonds.
Adhesive	A non-metallic substance capable of joining materials by surface bonding (adhesion), and the bond possessing adequate internal strength (cohesion).
Adhesive, Contact	An adhesive that is applied to both adherends and when allowed to become apparently dry will instantly develop a firm bond when applying a vigorous but not sustained pressure.
Adhesive, Heat-activated	An adhesive pre-applied to the adherends that is rendered tacky prior to use by application of heat and forms a bond on cooling under pressure.
Adhesive, Pressure Sensitive	An adhesive which in a dry state is permanently tacky at room temperature and adheres readily to surfaces under light and brief pressure.
Adhesive, Room Temperature Setting	An adhesive that sets in the temperature range 15 to 30°C.
Adhesive, Solvent	An adhesive in which the binder is dissolved in an organic solvent. (also called solvent-based)
Adhesive, Solvent - Activated	An adhesive pre-applied to an adherend that is rendered tacky immediately prior to use by the application of solvent.
Bond	A joint between adherends achieved by an adhesive. To join adherends by means of an adhesive.
Bond Strength	The stress necessary to bring an adhesive joint to the point of failure with failure occurring in or near the plane of the bond-line.
Catalyst	A substance generally used in small proportions that changes the rate of a chemical reaction, and in theory remains unchanged chemically at the end of the reaction.
Cohesion	The state in which the particles of a single substance are held together by primary or secondary valence forces.
Composite	An inhomogeneous material created by the synthetic assembly of two or more materials.
Cure	To change the physical properties of a material (usually from a liquid to a solid) by chemical reaction, by the action of heat and catalysts, alone or in combination, with or without pressure.
Curing Agent	See Hardener.

Exotherm	The heat given off by a chemical reaction.
Extender/Filler	An inert ingredient added to a resin formulation to modify the flow characteristics and mechanical properties of the adhesive.
Failure, Adhesive	The failure of an adhesive bond such that the separation appears to be at the adhesive/adherend interface.
Failure, Cohesive	Failure within the body of the adhesive, i.e. not at the interface.
Film Adhesive	An adhesive in film form, with or without a carrier.
Glue-Line Thickness	Thickness of the fully cured adhesive layer, (also called bond line thickness).
Hardener	A chemical added to a thermosetting resin for the purpose of causing curing or hardening. Amines and acid anhydrides are hardeners for epoxy resins. Such hardeners are a part of the chemical reaction and a part of the chemical composition of the cured resin. The terms hardener and curing agent are used interchangeably. Note that these differ from catalysts, promoters, and accelerators.
High Energy Surfaces	Thermodynamically, typical high energy surfaces are found on clean ceramics and metals.
Hot-Melt Adhesive	A thermoplastic adhesive that is applied in the molten state and forms a bond on cooling to a solid.
Joint	A junction of two adjacent adherends.
Low Energy Surfaces	Thermodynamically, typical low energy surfaces are found on plastics and composites and are difficult to bond to, without some surface treatment.
Multi-resistant bonding	Bonding where a joint, which may or may not be structural, needs to withstand other environmental forces, e.g. it could maintain its integrity and still be resistant to the effects of salt water spray, temperature cycling, and vibration.
Pot Life	The period during which a multipart adhesive can be used after mixing the compounds.
Primer	A chemical coating which may be applied to an adherend prior to application of adhesive, to stabilise a pretreated surface, to improve adhesion and/or to improve durability, e.g. performance in hot/wet environments.
Resin	A solid, semi-solid or liquid, usually organic material that has an indefinite and often high molecular mass and, when solid, usually has a softening or melting range and gives a conchoidal fracture. In a broader sense, the term is used to designate any polymer that is the basic material for plastics.
Sealant	An adhesive material, used to fill gaps where movement may occur in service and, when set, has elastic properties, e.g. silicone window frame sealants. The term is also used for a material filling a void against the ingress or egress of a fluid under pressure, e.g. anaerobic engine block flange sealants.

Shelf Life	The time of storage under stated conditions during which an adhesive may be expected to retain its working properties.
Structural	The term used to describe a bond, or an adhesive, if it is capable of sustaining in a structure, a specified strength level under a combination of stresses for a long period of time. The combination of stresses may include peel and shear forces, fluctuating loads, environmental exposure, or steady load.
Tack	The property of a material that enables it to form a bond immediately on contact with another surface which may be an adherend or another layer of adhesive.
Thermoplastics	Plastics capable of being repeatedly softened by increases in temperature and hardened by decreases in temperature.
Thermosets	Polymers or copolymers which, when cured by heat or other means, change into substantially infusible and insoluble products.
Thixotropy	A decrease of the apparent viscosity under shear stress, followed by a gradual recovery when the stress is removed. The effect is time-dependent.
Time, Assembly	The interval between adhesive application to the adherends and the initiation of heat and/or pressure of the setting process in the assembled joint.
Time, Curing	The period of time during which an assembly is subjected to heat or pressure, or both, to cure the adhesive.
Untreated Surface	A surface which has not been cleaned (may still be in the state as supplied by the manufacturer).
Viscoelasticity	The stress response of a material acting as though it were a combination of an elastic solid and a viscous fluid with flow dependent on time, temperature, load and rate of loading.
Viscosity	The property of a material to resist deformation increasingly with increasing rate of deformation.
Wetting	The ability of a liquid (adhesive) to spread on a specific solid surface.
Working Life	See pot life.
Wicking	The transport of a low viscosity adhesive into a pre- assembled joint. The transport of moisture along the adherend/adhesive interface, often leading to failure.