

EAA Aluminium Automotive Manual – Joining

9. Adhesive bonding

Content:

9. Adhesive bonding

9.0 Introduction

9.0.1 Adhesive joints

9.0.2 Benefits of adhesive bonding

9.0.3 Adhesive bonding in the automotive industry

9.0.3.1 Sealants

9.0.3.2 Anti-flutter adhesives

9.0.3.3 Hem flange bonding

9.0.3.4 Structural bonding

9.0.3.5 Interior bonding

9.0.3.6 Glass bonding

9.0.3.7 Repair bonding

9.1 Design aspects

9.1.1 Design for adhesive bonding

9.1.2 Types of Adhesive Bonds

9.1.3 Design for adhesive bonding

9.1.4 Structural analysis and modelling

9.2 Adhesive selection

9.2.1 Selection criteria

9.2.2 Type of adhesives

9.2.2.1 Two-step acrylic adhesives

9.2.2.2 Cyanoacrylates

9.2.2.3 Epoxy adhesives

9.2.2.4 Hot melt adhesives

9.2.2.5 Polyurethane adhesives

9.2.2.6 Elastomeric adhesives

9.2.2.7 Anaerobic adhesives

9.2.2.8 Plastisols

9.2.2.9 Rubber adhesives

9.2.2.10 Modified phenolics

9.2.2.11 Pressure-sensitive adhesives

9.3 Adhesive application

9.3.1 Application techniques

9.3.2 Adhesive curing

9.4 Surface pre-treatment for adhesive bonding

9.4.1 Aims of a surface pre-treatment

9.4.2 Surface pre-treatment of aluminium alloys

9.4.2.1 Surface cleaning

9.4.2.2 Conversion-Coating Systems

9.4.2.3 Thin anodised films

9.4.2.4 Primer coating

9.4.2.5 The total system approach

9.5 Properties of adhesively bonded aluminium alloys

THE ALUMINIUM AUTOMOTIVE MANUAL

- 9.5.1 Mechanical and thermal properties of adhesives
- 9.5.2 Performance of adhesively bonded joints
- 9.5.3 Long-term durability
 - 9.5.3.1 Effect of moisture on a bonded joint
 - 9.5.3.2 Test methods for evaluating adhesive bond durability

9.0 Introduction



Robotic application of structural adhesive to aluminium sheet

Adhesive bonding is a reliable, proven and widely established technique for joining metals, plastics, composites and other materials. In recent years, adhesive bonding has been used more and more in automotive joining for a variety of components including closures and structural modules. The application of adhesive bonding instead of or in combination with conventional joining technologies enables a significant weight reduction of the vehicle, an increase of the body stiffness, improved crash performance/safety and enhanced NVH characteristics. In addition, adhesive bonding allows the realisation of new, innovative designs, in particular mixed material designs including high strength steels, non-ferrous metals, plastic and composites offering further lightweighting potentials. Also possible are the introduction of new, efficient assembly opportunities.

In fact, the introduction of adhesive bonding into car manufacturing can be viewed as one of the key enabling technologies for the production of aluminium closures and all-aluminium car body structures. In general, exclusively bonded joints are today not applied for structural purposes. However, several automakers have demonstrated that aluminium bodies assembled using adhesives in combination with self-piercing rivets, spot welds or other joining techniques equal or exceed conventional stiffness requirements (see 10.1.2). Purely adhesively bonded joints show limited strength in peel and cleavage and thus punctiform joints provide peel-stopping points in the case of overload (e.g. crash). The combination of the assembly methods ensures a high fatigue strength and offers economic benefits because there is no need for fixtures during the polymerisation of the adhesive (and – compared to purely adhesive bonding – assembly times can be shortened).

Adhesive joining is defined as the process of joining parts using a non-metallic substance (adhesive) which undergoes a physical or chemical hardening reaction causing the parts to join together through surface adherence (adhesion) and internal strength (cohesion). Ideally, the joining surfaces should be clean (although adhesives are also often applied over stamping lubricants) and generally require proper preparation of the aluminium surface. Furthermore adhesives require time and/or temperature to cure (harden). However, the cure can also be achieved in inevitable post-processing steps, such as during the paint cycle.

Today, many different types of adhesives, pre-treatment methods and processing techniques are available and on-going developments are looking for further improvements. The selection of the optimum solution involves a close consideration of multiple criteria, close contact with the respective suppliers is recommended. In some cases, extensive experimental testing may be required.

9.0.1 Adhesive joints

Adhesive joints are multi-layer organo-metallic materials whose strength depends on both the geometrical design and loading type as well as the material properties of the joined components, the adhesives and/or the characteristics of the bonded surfaces. A direct combination of these factors in order to determine the characteristics of the bond is, however, generally not possible.

The characteristics of an adhesively bonded joint are basically determined by three components:

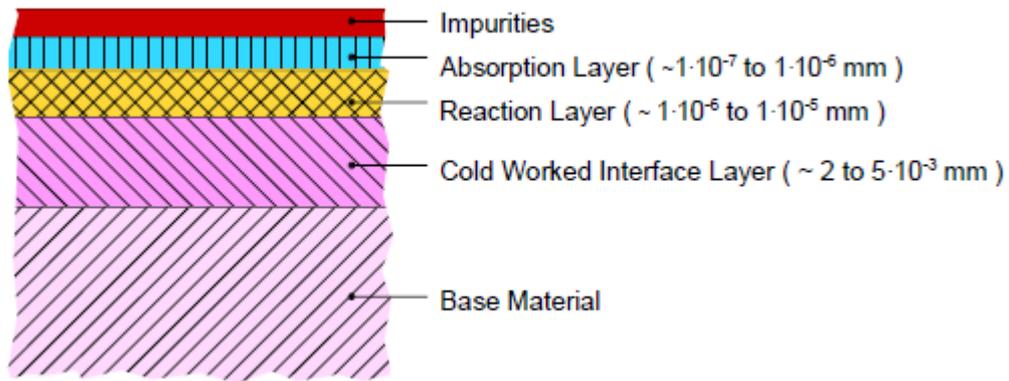
- The wetting behaviour of the surfaces to be joined
- The bonding (adhesion) of the adhesive to the joined component
- The inner strength (cohesion) of the adhesive.

Adhesion is the result of mechanical interlocking between the adhesive polymer and the rough material surface (mechanical adhesion) and the physical and/or chemical interaction between the adhesive and the material (material-specific adhesion). Mechanical adhesion is determined by the (micro-) morphology of the joining surfaces, i.e. the anchoring of the hardened adhesive in the material surface.

Material-specific adhesion summarises the attractive forces between the molecules of the adhesive and the surface(s) to be bonded. These forces have a maximum range of about 0.5 nm. Thus, a necessary condition for attaining high adhesion forces is that the adhesive is able to wet the material surfaces spontaneously and uniformly. This can be achieved by the selection of an adhesive with an appropriate viscosity and a lower surface tension than the material(s) being bonded. In general, polymers and other organic materials have low surface energy while metals and ceramics have high surface energy. Therefore, careful consideration should be taken when bonding plastics and composites to aluminium. Either the adhesive needs to have a low enough surface energy or the surface of the plastic needs to be modified such that it can accept the adhesive.

An important factor to keep in mind is that the incoming aluminium surface typically shows multiple surface chemistries due previous processing. This can include both inorganic and organic contaminants including, but not limited to, lubricants, oxides, dust, and dirt. These contaminants will prevent the adhesive from bonding to the base material and must be removed to prepare the surface for bonding. If the adhesive would be simply applied to the typical aluminium surface, the adhesive would not form a long-term bond to the base material, but to impurities and reaction products present on its surface. The surface contamination will reduce bond strength by interfering with the ability of the adhesive to form a proper bond (resulting in a weaker bond or a reduced bond area).

For this reason, aluminium-based materials are normally subjected to a suitable cleaning and surface treatment before bonding. It is absolutely necessary to first remove impurities in a surface layer of undefined thickness (i.e., dust, dirt, oil, grease, fat, water). Also the subjacent inactive adsorption layer created by foreign molecules (i.e., water, gases) must be removed. Furthermore, the native (heat-generated) oxide layer ("reaction layer") which is both inert and inhomogeneous must be generally replaced as well.



Typical aluminium sheet surface layers

Adhesive bonding in the automotive industry presents an interesting challenge. General instructions for adhesive bonding usually include measures such as “clean the mating surfaces thoroughly”, “use an adhesion promoter” and/or “use a primer”. Priming can be an appropriate surface coating that provides a more consistent, bondable surface. An adhesion promoter may activate the surface, providing chemical groups ready to latch onto the adhesive when applied. However, both the use of adhesion promoters and primed parts is usually limited to adhesive bonding processes in final assembly operations (e.g. the attachment of interior and exterior components to an already lacquered car body). Such measures are not used in the body shop.

The surfaces of all the aluminium parts (sheets, extrusions and components ready-to-assemble) which will be adhesively bonded in the body shop are generally cleaned and properly pre-treated by the material or part supplier. But in manufacturing of the body-in-white, there is no specific surface cleaning of the components before assembly (i.e. before hem flange bonding and structural bonding). Proper cleaning of the body-in-white is only carried out prior to painting.

In the stamping plant, only a light cleaning of the pressed panels may take place occasionally. Consequently, it is most important that the adhesives applied in body-in-white manufacturing are compatible with the protective coatings and/or processing lubricants applied in any subsequent operations at the material manufacturer or in the press shop (e.g. during finishing, transport and stamping). The adhesive must be able to displace, absorb or otherwise tolerate any specifically applied coating. Proper care must be taken to avoid any additional contamination of the material surface.

9.0.2 Benefits of adhesive bonding

The application of structural adhesives, alone or in combination with other joining methods, enables significant improvements of the overall efficiency and effectiveness of a car body structure and is therefore a key element of aluminium-based lightweight design solutions. The use of adhesives in automotive manufacturing processes offers the designer additional possibilities to exploit new, innovative design and manufacturing concepts. Adhesives are particularly popular for light-weight constructions, where thin-walled parts (wall thickness < 1 mm) must be joined. Adhesive bonding also allows combining different types of materials (e.g. aluminium with other metals, plastics and composites) which otherwise could not be reliably joined or would require additional measures (e.g. to avoid galvanic corrosion effects). Adhesives generally feature excellent adhesion to properly surface pretreated aluminium and a wide range of other substrates including steel, magnesium, plastics and composites. For mixed material structures, most interest is in joining aluminium to thermoset composites, such as carbon fibre reinforced epoxy composite. However, aluminium can be bonded to thermoplastic composites as well.

In adhesive bonding, unlike most other joining methods, the bulk of the material is not involved in the joining process. Adhesive bonding is an attachment to a surface and does not interfere with the aluminium metallurgy or results in thermally or mechanically weakened metal zones. Compared to a conventionally joined structure, the entire interfacial surface in the joint can be bonded. The uniform stress distribution over the entire bond face has a very positive effect on the static and dynamic

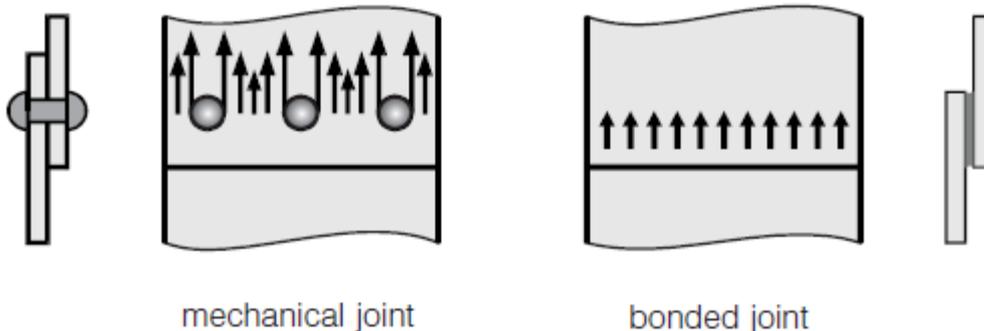
THE ALUMINIUM AUTOMOTIVE MANUAL

strength of the joint, i.e. the static and dynamic stiffness of the vehicle structure is significantly increased. More rigid body structures have higher resonance frequency modes and faster structural damping, providing improved vehicle handling and NVH characteristics (reduced vibrations and noise). In particular in combination with other joining methods, also crash performance and fatigue strength are improved by adhesive bonding, allowing an additional weight reduction of the body structure (e.g. by the application of lower material gauges).

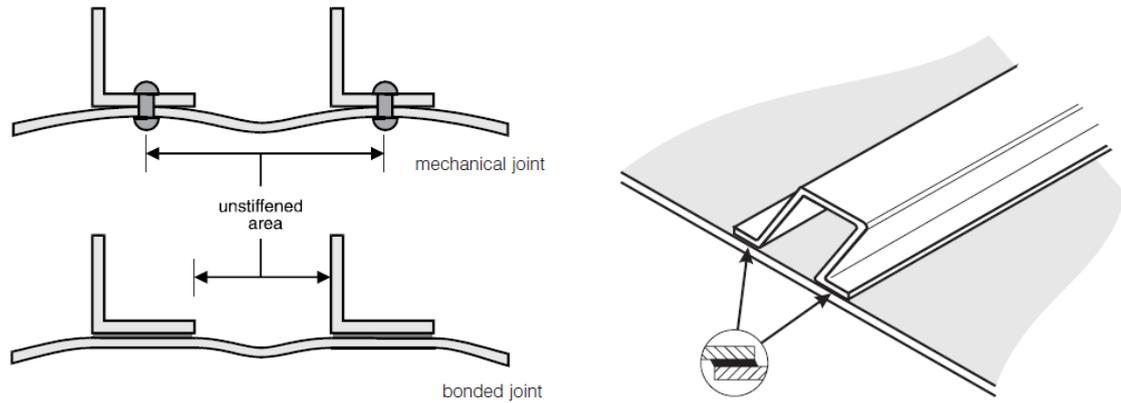
Apart from pure strength transfer, adhesively bonded interfaces can fulfil additional functions, including damping or insulation. Adhesives can also act as sealants, preventing loss of pressure or liquids and blocking the penetration of condensation water. Proper gap filling eliminates crevice corrosion and galvanic corrosion of dissimilar joints is hindered by the presence of an insulating layer. Properly selected adhesives can join materials with different coefficients of thermal expansion (as long as the coefficients of thermal expansion are not radically different). The adhesive may also act as an electrical and thermal insulator.

Another advantage of the adhesive bonding technology compared to conventional joining techniques is the improved aesthetics of the final assembly (although there may be a need for fillet control in order to obtain a completely “clean” aesthetic which can be accomplished by precise metering during application). There are no visible weld seams, rivet heads or discolorations and pre-treated and/or lacquered surfaces are not damaged. Thus, adhesive bonding may minimize or eliminate secondary operations like grinding and polishing. Most beneficial is also its gap filling potential. Adhesives can bridge large gaps between panels and improve the overall appearance compared to other joining methods. Therefore, in many cases, joining and sealing operations can be combined.

Properly designed adhesively bonded joints have distinct advantages over those made by mechanical or thermal joining methods. Whereas spot welding and riveting result in localized stress peaks, adhesive bonding achieves uniform distribution and absorption of stress loads. Adhesive bonding eliminates holes or other local disruptions as observed in connection with mechanical joining techniques. The cured adhesive ensures a uniform stress distribution which leads to strong and stiff joints with improved fatigue performances. A riveted joint, for example, is highly stressed in the vicinity of the rivets and failure tends to initiate in these areas of peak stress. Similar, inhomogeneous stress distributions are observed with other punctiform joining methods. A continuous welded joint is, like a bonded joint, uniformly stressed, but the metal in the heat affected zone will have undergone a change in performance. In addition, adhesive bonding enables the design of smooth external surfaces and integrally sealed joints with minimum sensitivity to crack propagation.



Adhesive bonding offers also additional design possibilities over conventional joining methods. As an example, large panels of thin gauge material can be more effectively stiffened by bonded stiffeners. Towards the edge of the sheet, the top hat stiffener may be cut away in order to reduce stress concentrations even further.



Stiffening of large panels

In automotive assembly, the rapid and easily automated application of adhesives proved to be a clear benefit. For example, whereas thermal joining methods can cause distortion of the individual components which may affect the overall assembly performance, adhesive bonding does not distort sufficiently inflexible parts.

However, there are also some limitations. A basic limitation compared to some mechanical joining methods is that adhesively bonded structures (similar to welded structures) cannot be easily dismantled for in-service repairs. Care must be given to use of adhesive joining on thin metal automotive panels where localised modulus (strength) variations may increase the potential for appearance concerns known as “read-through”. The biggest problem is that assembled joints must be supported until the adhesive has sufficiently cured. This can significantly slow down the assembly process as it is necessary to allow for the relative slow strength build-up during assembly and processing of adhesive bonds. An alternative is to use temporary fixtures that ride along with the assembly processing. The generally applied solution is to combine adhesive bonding with (resistance or laser) spot welding or with mechanical joining techniques such as, for example, self-piercing riveting or clinching as part of the overall assembly process. Combining welding or riveting with adhesive bonding is known as weld-bonding or rivet-bonding, respectively. These methods are most commonly used today and will be covered in more details under “10. Hybrid joining techniques”.

9.0.3 Adhesive bonding in the automotive industry

Adhesive bonding has been applied in automotive manufacturing for a long time. However, adhesive bonding for structural application is relatively new. Today, the variety of adhesives on the market is enormous. The biggest problem is the selection of the optimum adhesive for a specific application, depending on its processing behaviour (application and curing characteristics) and the final service performance (in particular long-term stability).

Moreover, development activities are going on and improved adhesives, surface preparation methods and application systems are continuously introduced giving body designers yet even more cost-effective and/or higher-performing assembly tools. Considering the amount of sealants and caulks used in modern car body construction, a most promising development route is the combination of the role of sealants with the function of adhesives in the joints and thus gain improved structural performance at little additional cost.



Adhesive application to light metal intake manifold
(Source: Henkel)

9.0.3.1 Sealants

Before paint is applied to the car body, joints and crevices must be sealed to prevent possible damage of joined substrates by protecting against unfavourable environmental influences, penetration of air, moisture or dust, leakage of hazardous materials and gasses, corrosion, etc. They also allow simplified designs and, in many cases, seam sealers are also used to provide a superior painted finish.

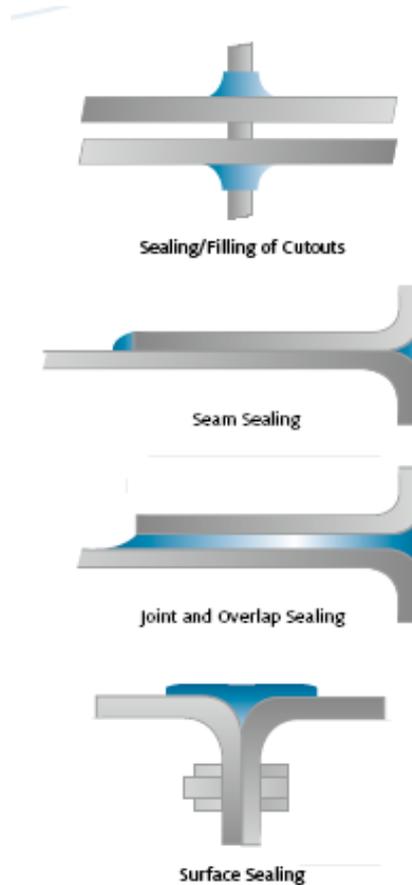
Seam-sealing materials must show very good corrosion resistance and gap filling properties. Additional requirements include the ability for smooth manual and automatic application, stability and wash out resistance during cleaning, electro-coating and lacquering, and durability in service.



Manual and automatic application of sealants
(Source: Sika / Henkel)

THE ALUMINIUM AUTOMOTIVE MANUAL

Sealants form a “bridge” between different part surfaces. The strength of the bond depends upon adhesion of the sealant to the surface of the substrate and cohesion (strength within the sealant itself). The physical and chemical properties of sealants depend to a large extent on the selected raw material basis.



Basic sealant types

(Source: Henkel)

The basic difference between adhesives and sealants is that sealants typically have lower strength and higher elongation than adhesives. Since the primary objective of a sealant is to seal assemblies and joints, sealants need to have sufficient adhesion to the substrates and resistance to environmental conditions to remain bonded over the required life of the assembly. When sealants are used between substrates having different thermal coefficients of expansion or differing elongation under stress, they need to have adequate flexibility and elongation. Low shrinkage after application is often required too.

Sealants generally contain inert filler materials and are usually formulated with an elastomer to give the required flexibility and elongation. Normally, they have a paste consistency to allow the filling of gaps between substrates. Conventional sealants are one-component adhesives which generally rely on the moisture in the air to cure.

Many newly developed sealants are designed to also perform structural functions. They are partially cured in the assembly process with full curing during the paint processing. Urethanes, epoxies and vinyl-plastisols are widely used as adhesives/sealants. Also solid hot melts are growing in popularity.

9.0.3.2 Anti-flutter adhesives

The function of an anti-flutter adhesive is to reduce or eliminate any “fluttering” or vibration of the outer and inner panels relative to each other. Anti-flutter adhesives are commonly used on horizontal closure panels such as bonnets, trunk lids or roofs with less application on vertical panels like doors.

A characteristic of anti-flutter applications is the relatively large thickness of the bond line (up to several millimetres). In addition, the anti-flutter adhesives are generally not applied as a bead; but as local “drops” strategically spaced across the inside surface of the outer panel, aligning with the shape of the inner panel. The applied anti-flutter adhesives have a low modulus and a lower strength than for example hem flange adhesives. The very low modulus enables anti-flutter adhesives to function as a stress-relief interlayer, improving the read through performance on thin panels.



Application of anti-flutter adhesive/sealants

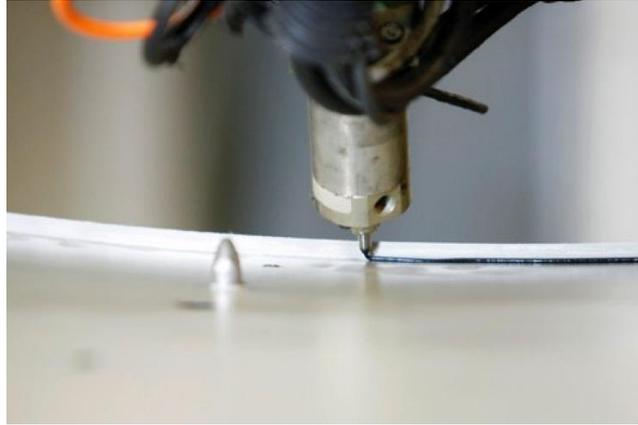
(Source: Sika)

The materials used in this application include vinyl plastisols, elastomeric or rubber-based, and warm-applied adhesives. New elastomeric rubber based technologies exist, known as high damping foams, which provide additional acoustic (NVH) performance, by converting the kinetic energy of vibration into thermal energy. A specific surface preparation is generally not necessary.

9.0.3.3 Hem flange bonding

The closure panels, i.e. doors, bonnets, trunk lids, tailgates, etc., of cars are usually made from an outer panel which is hemmed (or clinched) over an inner panel around its periphery. Whilst hemming alone would produce sufficiently strong mechanical joints, adhesives are widely used in these flanges to provide improved strength, stiffness, crash performance and corrosion protection.

Hem flange bonding takes place in the body shop, i.e. before painting. At this moment, the stamped panels are usually covered with processing lubricants (rolling oil, drawing oils or dry lubricants, etc.). Residues of these processing lubricants will be present when the adhesive is applied since before hemming, the pressed panels will be subjected only to a light cleaning step, if at all. Therefore hem flange adhesives have to be compatible with the lubricants applied in earlier processing steps as well as other potential contaminations.



Adhesive application for hem flange bonding

(Source: Sika)

After the adhesive is applied to the outer panel either as an extruded bead or a sprayed film, the inner panel is positioned and the hem flange is formed. Hem flange adhesives are applied using swirl, bead or fine jet nozzles. In order to avoid “zero gap” in the hem flange, hem flange adhesives often contain glass beads to ensure constant distance between outside and inside panels. A hem flange includes a very thin adhesive film (around 0.1 mm). Bead size is carefully controlled in order to completely fill the bond line, but to avoid that excessive adhesive is squeezed out as it would contaminate the equipment.

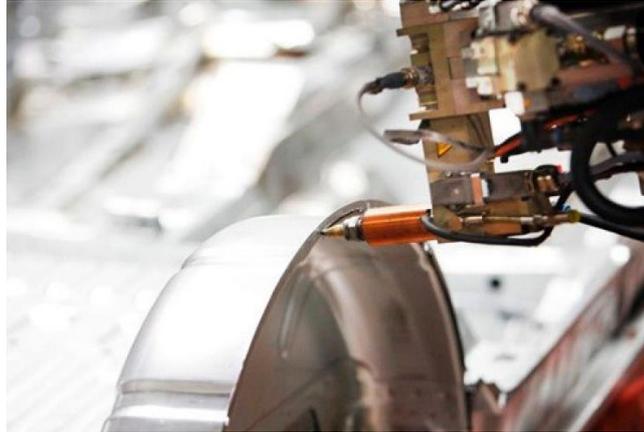
A cure step may be introduced at this stage, such as induction curing. This can be a full cure or just enough to prevent any movement of inner to outer panel during subsequent processing. The induction process is a rapid cure technique that begins the chemical cross-linking process within the adhesive so it is “set”. The cure is usually not complete, but will be finished in the paint ovens. However, the resulting pre-gelling holds the adhesive in place and improves resistance to wash-out of the adhesive.

The most widely used hem flange adhesives are one-part epoxies. They are sufficiently thixotropic that they stay within the bond line through application, mating of the inner and outer panels, attachment of the closure parts to the body-in-white, and movement through the paint line until final cure in the paint ovens.

In some applications, an elastomeric adhesive/sealer that functions both as a hem flange adhesive and an anti-flutter adhesive is used. Also two-part epoxies are used as hem flange adhesives. In this case, cure starts under ambient conditions and is completed in the paint ovens. Specific formulations of two-part epoxies improve wetting through lubricant films allowing hem flange bonding without any lubricant removal. Furthermore, improved adhesives have been produced with higher modulus (to increase body stiffness), instant grab (to eliminate the need for extra fixings and alignment aids) and more rapid development of green strength.

9.0.3.4 Structural bonding

Structural adhesives must be able to form and sustain a strong bond between the adherents in various environmental conditions over a long period of time. The majority of current automotive bonding applications are based on epoxy adhesives. This is due to the combination of various advantageous characteristics such as oil absorption capacity, good wash-out resistance, durability, and outstanding mechanical characteristics across a wide temperature range. An important requirement is also good processing performance (automated applicability, compatibility with mechanical joining techniques, resistance spot welding, etc.). While for pure stiffening applications the modulus of the adhesive is most important mechanical parameter, a combination of high modulus and high flexibility is essential for adhesives applied to improve vehicle component behaviour under high strain rates. Both parameters are important for optimum distribution of stress, optimum energy transfer between outer panel and carrier and broadening of the deformation area.



Structural bonding in the body shop

(Source: Sika)

Special impact resistance-modified epoxy structural adhesives allow additional load path-optimization, thus further improving crash performance. They are mainly used for structural bonds in the car body, but also in hem flange bonding for closures. Compared to previous generation structural adhesives, new generation adhesives show greater elongation at fracture, reduced bonding strength loss after corrosion, and reduced loss of dynamic peel strengths at low test temperatures.

In special applications, two-component polyurethane adhesives are used. Polyurethane adhesives are characterized by high strength and stiffness values at high elongation levels, resulting in improved impact and fatigue properties of bonded joints. Choices in adhesive chemistry may be influenced by surface conditions (absence of soils and oxide layers) and application process conditions.

In addition to the established epoxy systems, innovative rubber-based structural adhesives with glass transition temperatures of over 90° C are becoming increasingly popular due to an attractive cost-benefit ratio. Many closures are bonded with low modulus rubber-based adhesives. These adhesives, however, show some disadvantages over epoxy adhesive systems. The static and dynamic strengths are significantly lower than epoxy adhesives and they are generally less corrosion resistant. Also their temperature resistance is limited as their glass transition temperature is at the upper limit of the operating temperature range of the vehicle.

The relatively high elastic modulus of epoxy resin-based structural adhesives can result in read through effects when bonding exterior panels. Since sheet thicknesses have continuously decreased over recent years, read through becomes an increasingly relevant issue. A low-modulus adhesive can prevent such problems. Consequently, very flexible epoxy resin adhesives with low modulus have been developed which possess significantly higher static and dynamic characteristics than rubber-based adhesives. The new adhesive technology unites sealing and reinforcing characteristics in a single product. This is an especially significant improvement in the application of multi-material joining where both adhesive and sealing (insulating) characteristics are required to prevent the development of corrosion in the joint.

9.0.3.5 Interior bonding

Bonding applications for the interior of cars include a wide variety of substrates, adhesives, sealers, and requirements. Although most applications can be considered as trim bonding, there are also some with structural character. For example, the headliner may be designed in such a way that it contributes to the structural integrity of the roof.

Bonding applications for the interior of cars occur in the final assembly stage of the vehicle assembly plant. The bonding process needs to be as clean, quick, and as easy as possible. Therefore, cyanoacrylates adhesives, pressure sensitive adhesives, tapes, and hot melts are most popular. Two-part epoxies that cure at ambient temperatures have limited application. New technologies

receiving customer acceptance include hybrid cyanoacrylate-epoxy based adhesives which produce rapid fixture capability with more robust and longer term joint performance.

9.0.3.6 Glass bonding

There are several areas of glass bonding, such as windshield, rear window, side windows, or headlamps. In earlier applications, the primary function was to keep the glass in place and to act as a sealant.

New structural requirements take advantage of the large bond area and the strength of the glass to make the joint load-bearing and thus part of the load bearing structure. Therefore stronger adhesives/sealants are needed, and urethanes are usually chosen for these applications. They offer the required strength as well as the flexibility to bond two materials with very different expansion coefficients and can seal against moisture.

The adhesive can be one- or two-part polyurethane, with the second part more of an accelerator since the adhesive will eventually cure on its own in the presence of moisture. Other adhesives are also being investigated. Innovative direct glazing technologies are now available that eliminate the need for application of surface primers over painted surfaces



Windshield application

(Source: Sika)

9.0.3.7 Repair bonding

In many repair situations, a replacement part will need to be attached to the vehicle. Adhesives may be involved in the manufacture of a new part, which is then employed as a replacement unit in the repair shop. For these applications, the same or similar adhesives as used in the original joint will be used, as the part is prepared before shipping to the repair shop. Examples include replacement hoods, rear deck lids or roof panels where adhesively bonded flanges or hems may be present.

For the repair of structural members, there is generally a lack of high temperature curing facilities in the repair shop. The selection of adhesives for structural repair is likely to be limited to two-part epoxy formulations, but with significantly reduced joint strength and performance compared with the adhesive used in original manufacture. Consequently, this will lead to relatively low strength repair bonds compared to welded alternatives. Hence, structural bonding repairs should always be supplemented by mechanical reinforcements such as rivets, screws, clinches, etc.

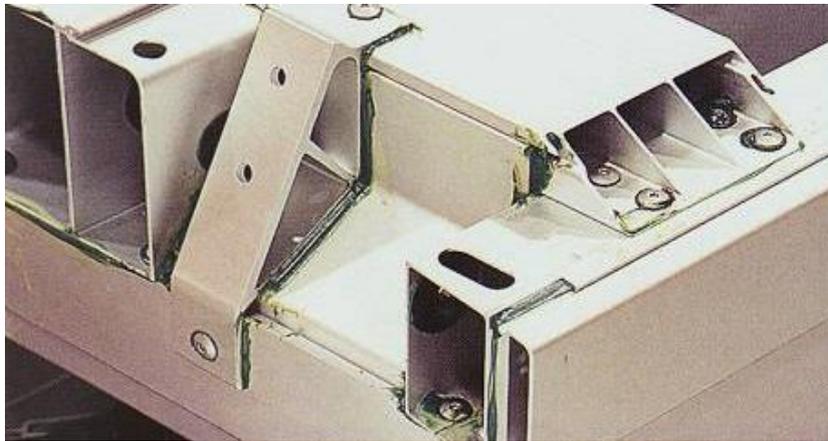
Since the staff of repair shops will likely have limited experience in the use of adhesives and metal preparation techniques, bonding practices must be simple, safe and quick. In addition, the aluminium surface pre-treatment techniques originally used in automotive manufacturing are generally not applicable. Therefore special methods for local surface pre-treatment will have to be applied (e.g. flame spraying (Pyrosil® technology), modified grit blasting techniques or manually applied pre-treatments (Bonderite® /Prep-n-Cote)). It has been demonstrated that certain two-part epoxy

adhesives, used in conjunction with suitable in-situ cleaning/pre-treatment practices can provide a total system with very good bond durability performance. Such systems form the basis of a mechanically reinforced bonded joining technology for structural repairs.

9.1 Design aspects

When designing adhesive bonding applications, optimizing joint design is an important consideration. An adhesive joint requires sufficient surface contact between mating work pieces to allow for a squeeze-out effect, a tiny bead that squeezes out from between the clamped, mated surfaces. An understanding of the various possible joint designs for application is an essential step to finding the optimum bonding solution. During the design phase, particular attention must be paid to the potential mechanical loads (static and dynamic). Furthermore, assembly, manufacturing methodology, and cost factors must all be taken into account when proposing a joint design.

In some cases, suitable measures can be already taken in the design of the individual components, e.g. by proper adaption of the cross section of an extruded aluminium profile. Where tongue and groove type bonded joints are possible, properly designed aluminium extrusions may be often the best solution.

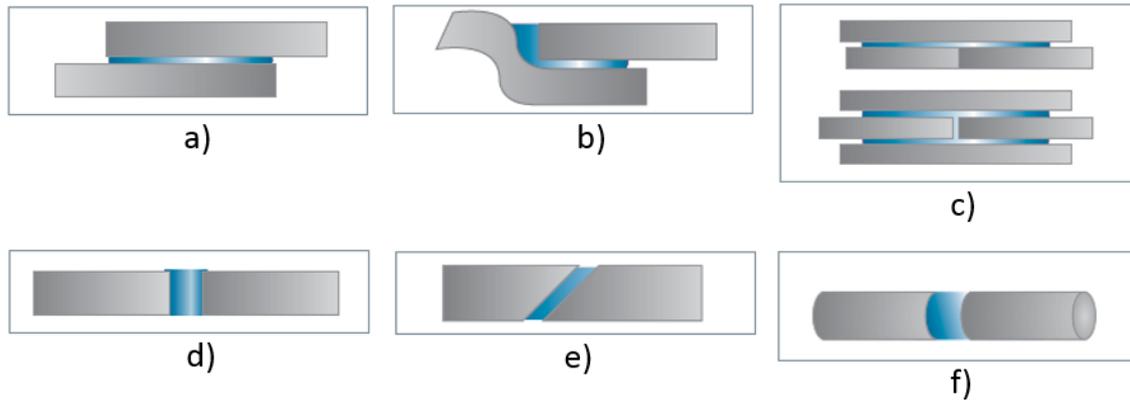


Aluminium extrusions designed for adhesively bonded joints

(Source: Lotus)

9.1.1 Design for adhesive bonding

Adhesive bonding involves the formation of a load-carrying element connecting the joined components. The material in the cured adhesive bond (plastic or rubber) is not as strong as aluminium. In practice, however, this can be easily compensated by providing a larger contact surface. An optimal joint design for adhesion is therefore an overlap configuration of sufficient width.



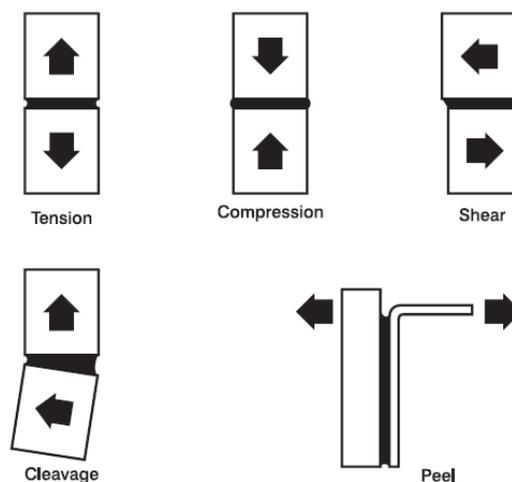
Types of adhesive joint design:

- a) Lap (overlap) joint, formed by partially placing one substrate over another
- b) Offset lap joint, similar to the lap joint
- c) Strap joint (single or double), a combination of an overlap and a butt joint
- d) Butt joint, formed by bonding two objects end to end
- e) Scarf joint (angular butt joint), cutting the joint at an angle increases the surface area
- f) Cylindrical joint, a butt joint between two cylindrical objects

(Source: Henkel)

Butt joints are generally not applicable for adhesive bonding; certainly not for components with small wall thicknesses. Scarf joints would be highly suitable for tensile-shear loading since the load distribution is in this case most favourable, however, they can be used only for parts with larger material thicknesses and are complicated to manufacture. In general, the practical alternative is a (single or double) strap joint which is a combination of an overlap joint with a butt joint.

Bonded joints may be subjected to a range of stresses including tensile, compressive, shear or peel and often a combination of these. Adhesives perform best in shear, compression and tension. They behave relatively poorly under peel and cleavage loading.



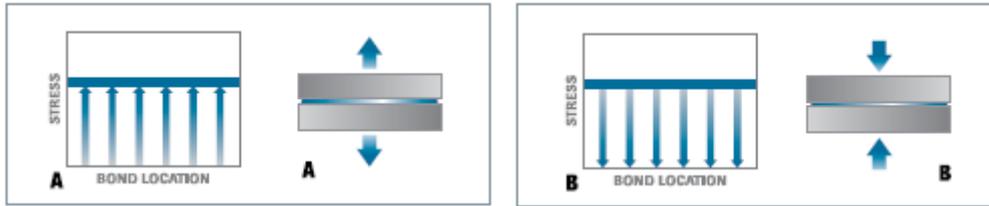
Loading types relevant for adhesive joints

A bonded joint needs to be designed so that that the adhesive is used to its fullest mechanical advantage. The main advantage of adhesive joining over welding, riveting and screw fastening is that the load is distributed more evenly at right angles to the loading direction. In the loading direction, however, this is valid only for scarfed joints. Within a given structure, the bond should be aligned so that it is stressed in its strongest direction. The design should reinforce the tensile,

THE ALUMINIUM AUTOMOTIVE MANUAL

compressive and shear stresses. For maximum strength, cleavage and peel stresses should be designed out of the joints as far as possible.

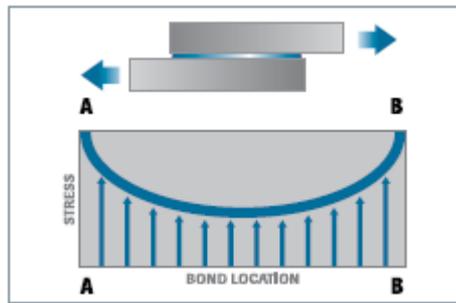
When an adhesive bond experiences a tensile or compression stress, the joint stress distribution is represented as a straight line. The stress is evenly distributed across the entire bond.



Joint stress distribution in tension (left) and compression (right)

(Source: Henkel)

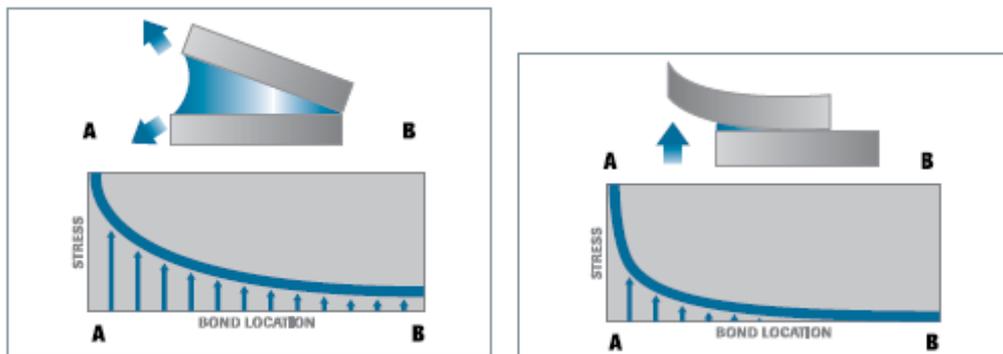
A shear stress results in two surfaces sliding over one another. On loading a simple lap joint, the main force resolves into a shear component along the plane of the interface with a peel component at right-angles. The stresses are highest at the edges of the bond causing strain and twisting. Adhesives accommodate high loads in shear because there is a large active joint area.



Shear stress distribution

(Source: Henkel)

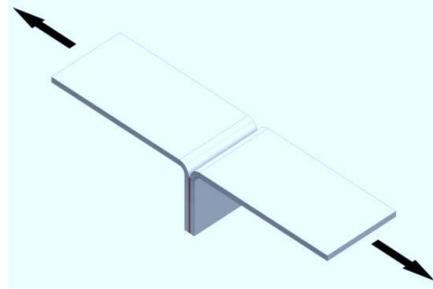
A cleavage stress occurs when two rigid substrates are opened at one end. When a flexible substrate is lifted (peeled) from the other substrate, a peel stress develops. Cleavage and peel loading concentrate the applied force at one end into a single line of high stress.



Cleavage (left) and peel stress (right)

(Source: Henkel)

Furthermore tensile loading resulting in peel or cleavage peel is not desirable for adhesive bonding. On the other hand, many joints designed for spot welding or riveting emphasize peel mode loading because welds and rivets perform relatively well in peel. As an example, the standard T (or coach) joint is not a suitable design for adhesive bonding. Therefore, the direct conversion of an existing joining system to adhesive bonding is not a good approach.

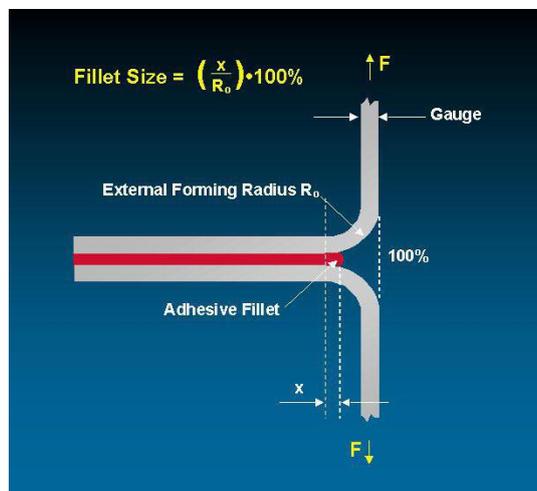


T-peel joint under tension

In most cases, the stress distribution throughout a T joint can be improved by leaving intact the small amount of resin squeeze-out and tapering the overlap to remove the sharp, right-angle ends. Appropriate design concepts which have proved most successful also exist for corner joints, closed-sectioned profile joints and tube joints.

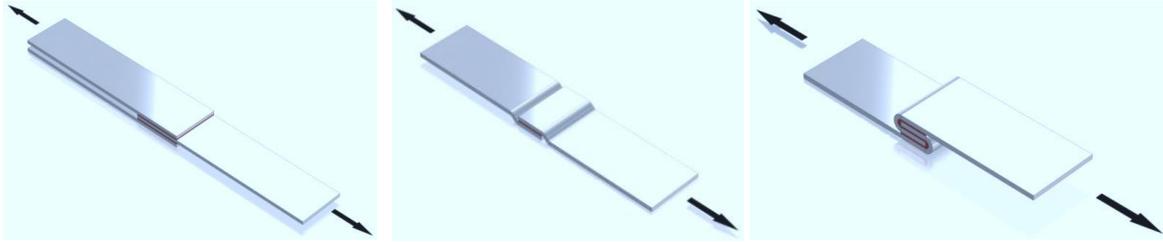
In the manufacture of automotive structures, however, a large percentage of adhesively bonded joints will be peel-type joints in order to enable the application of an additional joining method (e.g. clinching, self-piercing riveting, friction stir spot welding, laser stitch welding or resistance spot welding). The use of adhesive bonding in combination with spot-type joining techniques significantly increases the joint stiffness and will result in a positive contribution to the overall stiffness of the vehicle structure.

For this reason, the strength of bonded T-peel joints in peel must still be considered. The amount of adhesive in the fillet region has a considerable effect on the stiffness of the T-peel joint. As the fillet size increases, the strength of the T-peel joint also increases. During manufacturing, however, the fillet size will not be controlled and will be influenced by panel fit-up and alignment. It is therefore important to develop experimental test data based on a conservative fillet size.



Definition of fillet size in T-peel joint

Joints that favour shear loading are the best types for adhesive bonding. Some examples of shear joints that can be used in automotive construction are shown below. Aluminium, other metals, or composites can be successfully combined using any of these approaches.



Shear joints suitable for automotive design (from left to right): Double lap, Step (offset) lap, and Hem joint

The following design guidelines which should be considered when designing an adhesive joint:

- **Maximise shear/minimise peel and cleavage**

Justification follows from the stress distribution curve. Whereas in the case of shear, both ends of the bond resist the stress, stress is located at one end of the bond line for cleavage and peel.

- **Maximise shear/minimise tensile**

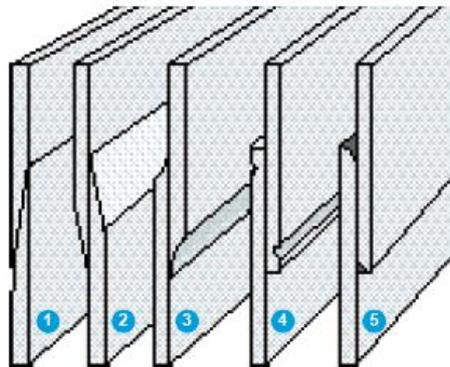
For compression and tension, stress is uniformly distributed across the bond. In most adhesive films, the compressive strength is greater than the tensile strength. Thus an adhesive joint is less likely to fail under compression than under tension.

- **Joint width more important than overlap**

The ends of the bond show a higher stress level than the centre of the bond. If the bond width is increased, stress will be reduced at each end and the overall result is a stronger joint. If the overlapping length is greatly increased, however, there is little, if any, change in the bond strength (“increase the joint width rather than the overlap area”).

Another aspect that must be considered when designing adhesively bonded joints is the fact that bond strength decreases with increasing temperature. Proper selection of the applied adhesive helps, but compared to conventional joining methods like welding or mechanical joining, the thermal degradation of adhesively bonded joints is nevertheless significant. It is also important to note that an adhesive can behave like rubber at room temperature, but can become like glass at subzero conditions.

Bonded joints distribute stress relatively well. However, stress is rarely evenly distributed across the entire surface area of a bonded joint. Generally, stress is greatest at the edges of the joint. The local concentration of any subsequent loading stress is the higher, the stiffer the chosen adhesive. In order to avoid unnecessarily high stress on the adhesive and the surface that has been bonded, the chosen adhesive should not be stiffer than necessary. Also thicker bonded joints reduce the concentration of stress at the edges of the joint. Thus, especially when using a stiff adhesive, it is important that the design spreads any load evenly throughout the bonded joint in order to reduce edge effects.



Lap joints modified to reduce stress at a joint's edges

(Source: Sapa)

9.1.2 Structural analysis and modelling

Finite element analysis (FEA) and fracture mechanics methodologies are routinely used for designing bonded joints. Bulk mechanical properties and single lap shear data taken off an adhesive technical data sheet are not valid for design purposes. The reported adhesive bulk properties do not reflect the true adhesive bond strength. Single lap shear data, while representative of relative performance, do not provide pure shear mode values. It is necessary to obtain genuine engineering design data from actual peel and shear tests. These measurements provide actual engineering data that reflect the surface condition expected to be used in practice.

For modelling, the interfacial regions between the adhesive and the bonded surface are often represented as viscoelastic elements rather than rigid elements. To model the bond, spring elements are placed at the interface. Spring elements are necessary because the load is applied through one side of the joint, into and out of the adhesive, and through to the other side of the joint through a viscoelastic fluid (adhesive), as opposed to a fairly rigid, homogeneous material (welds or rivets). Welds and rivets can be inserted into the model and defined as rigid elements, or another protocol commonly used by the analyst can be modelled. This is particularly important in modelling crash behaviour.

Modelling the adhesive joints as springs is, however, an inconvenient modelling procedure as spring properties are not intrinsic in nature and are not mesh-size independent. Modelling of adhesives with solid elements can provide good prediction of the mechanical behaviour of adhesively bonded joints, but is time-intensive and impractical for large vehicle models. Various attempts have been made to develop simplified finite element models; however, all these approaches have limitations and drawbacks. There is still a need for further developments before an efficient, numerical method for the simulation of the crashworthiness of an adhesively bonded car structure is available.

9.2 Adhesive selection

Identifying a suitable adhesive is a complex task due to the range of available adhesives and the specific application requirements. Such requirements can include specific structural and environmental performance, such as load transmission, media exposure, leak tightness, electrical conductivity, heat conductivity, and damping. This necessitates a holistic consideration of the entire process – from the design and surface pre-treatment – to integration into the relevant production process.

9.2.1 Selection criteria

When an adhesive is selected for a specific application, it is important to ensure that the chosen adhesive fulfils all the engineering and service requirements (good adhesion to the applied materials), static and dynamic strength (with defined levels of strength retention after environmental exposure), impact peel strength (especially at low temperatures), creep (ability to carry load at temperature), etc. Equally important, however, is to consider whether the processing characteristics of the adhesive are compatible with the planned assembly process. The adhesive must have sufficient fluidity and the necessary time to mould itself to the surface topography of the substrate. Fast setting, high-viscosity adhesives rarely permit this. In this case, it might be advisable to first apply a low-viscosity primer. Other relevant processing characteristics are related to the application and curing properties of the adhesive:

- What type of dispensing equipment is required; is the adhesive easily dispensed using automated and/or manual methods?
- Is special curing equipment (e.g. ovens or UV light sources) required?
- What is the influence of environmental factors (i.e. temperature and relative humidity) on the curing rate of the adhesive?
- How much time needs the adhesive to develop sufficient strength to proceed to the next step in the assembly process?

In addition to the correct chemical and mechanical properties of the adhesives applied in automobile fabrication, their robustness in the manufacturing system must be considered as well. The adhesive must be easy to handle, it must offer suitable rheological properties for automated application (pumpability, dispensability, etc.). Most important is also material consistency from batch to batch and storage stability. Furthermore, two-part adhesives must have a tolerance of off-ratio mixing.

Another aspect is sag and slump resistance during application. During assembly, there is always the possibility of larger gaps present between the flanges due to poor panel fit-up or misalignment. The adhesive should have sufficient gap bridging capability and the cured joint must offer consistent properties over a certain range of bond line thicknesses. Experience showed that for both single-lap and T-peel structural joints, there is very little joint property change over a bond line thickness range of 0.2 to 0.5 mm. Additional requirements exist if the adhesive should act simultaneously as a sealant.

Further complicating the adhesive application process are the unique needs of an automotive production line. Adhesives are applied to separately assembled parts (e.g. closure panels like bonnets or doors). These parts are then attached to the car body structure which may also include adhesively bonded joints. After completion of the body-in-white, the assembled structure will go through a cleaning and painting process before additional components are attached by adhesive bonding in the final assembly. The applied adhesives need to have the ability to stay in place during subsequent assembly processes as well during all the different surface treatment steps (i.e. wash-out resistance and electro-coat compatibility are generally necessary). Also required is proper planning and control of the curing conditions (e.g. time, temperature and/or humidity) at all steps.

An important aspect is the fact that adhesive bonding in structural joints is usually combined with a secondary joining technique (hybrid joining). As an example, when combined with mechanical joining methods, it must be ensured that the displacement of the adhesive does not lead to disturbances within the adhesive film. It is most important that the adhesive still completely protects the flange because any open gap may increase the corrosion risk. When combined with resistance spot welding, it must be ensured that the adhesive will not interfere with the formation of the weld nugget. The adhesive must be fluid enough to flow out of the weld area without leaving significant residue that would weaken the weld, but not so fluid that it escapes the joint area or contaminates the weld equipment. In this context, it must be kept in mind that the heat introduced during spot welding will also affect viscosity of the adhesive. Furthermore, the adhesive must not catch fire, smoke excessively, or produce any toxic gases.

9.2.2 Type of adhesives

Adhesives are generally classified by either the way they are used (specifically by the way they are setting) or by their chemical type. There are only three ways of setting (although combinations of these may occur):

- **Setting through drying** (i.e. the solvent or water evaporates). Since most of the drying must take place through the material, this adhesive type is not suitable for bonding aluminium to aluminium or other metals. However, it could be used for example for bonding porous materials to aluminium.
- **Setting through cooling**. Some of the drying adhesives can be heat activated. They are applied to one or both surfaces and dried. When joining, the adhesive is activated (melted) on one of the parts and quickly joined with the other. This type of adhesive (not to be confused with hot melts which are applied hot) enables rapid assembly, but is only suitable if one of the materials is readily deformable.
- **Setting through curing (chemical reaction)**: The two most common types of forced cure adhesive are one and two component systems. One component system adhesives are supplied in a ready to use form, which cures when exposed some external energy (heat, radiation or moisture). Two component system adhesives utilize the mixing of two different materials which creates a chemical reaction that causes the polymerization (curing or setting) of the materials.

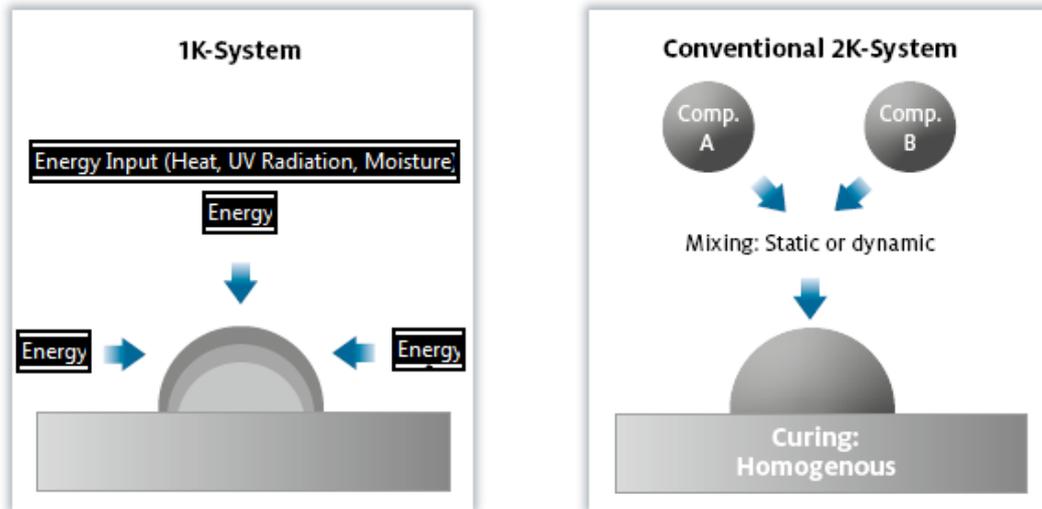
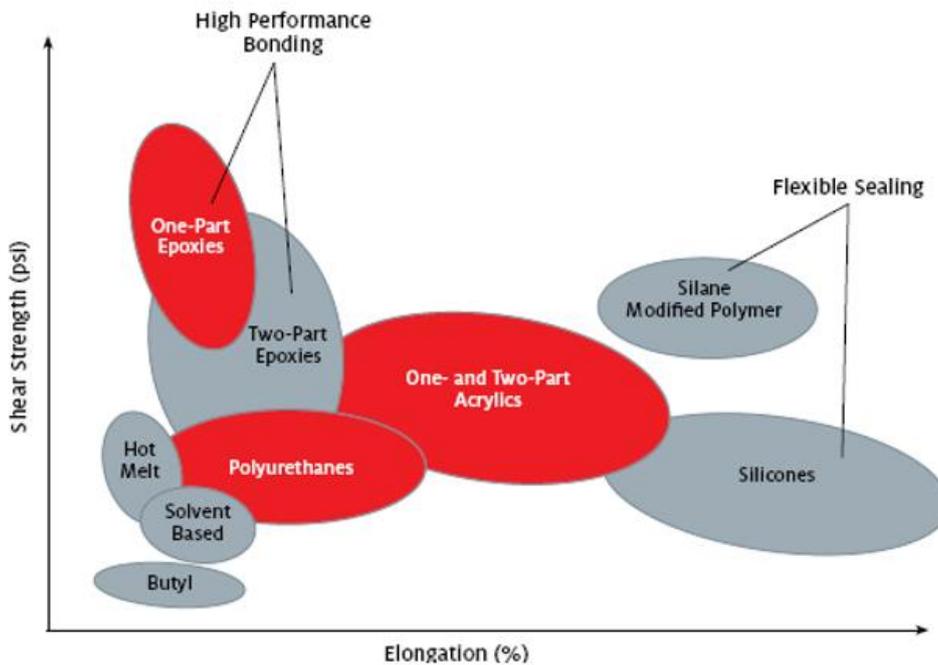


Illustration of adhesive curing methods

(Source: Henkel)

The strongest adhesives solidify by chemical reaction, with the less strong types hardening by a physical change. In the following, the most important types of adhesives are shortly described, for more detail please contact the adhesive suppliers.



Relationship of adhesive types to performance

(Source: Henkel)

9.2.2.1 Two-step acrylic adhesives

Two-step acrylic adhesives consist of a resin and an activator (“hardener”). The resin component is a solvent-free, high-viscosity liquid, the activator is typically a low viscosity liquid. When the resin and activator contact each other, the resin begins to cure very rapidly at room temperature (typical fixture times are 15 seconds to several minutes), depending on the gap width. The resin can be fully cured with light or heat (typical heat curing time 10 - 20 min at 150 °C). Heat curing normally offers higher bond strengths, improved thermal resistance and better chemical resistance.

Two-step acrylic adhesives require no mixing and bond to lightly contaminated (oily) surfaces. The hardener is generally spread on one surface and the adhesive on the other. These types of adhesives show high peel strength and toughness as well as good environmental resistance. They bond well to a range of materials, but are not particularly suitable where gap filling is required. They are best suited for small to moderately large surfaces.

9.2.2.2 Two-part acrylic adhesives

Two-part acrylic adhesives consist of a resin and an activator, both of which are normally high-viscosity liquids. The activator is chemically similar to that of a two-step acrylic, but it is delivered as a high viscosity liquid. The two components are mixed just prior to dispensing, i.e. a homogenous one-part material is dispensed. The curing times are somewhat longer than those which can be achieved with two-step acrylics. These adhesives can therefore also be used for thicker joints. For high volume applications, meter mix dispense equipment is used. Two-part acrylics cure at room temperature (5 – 30 min), but cure can be accelerated with heat. Contactless handling and good ventilation is required as the components have a strong smell.

Two-part acrylic adhesives offer high peel and impact strength as well as good environmental resistance and bond to moderately contaminated surfaces. As a consequence, acrylic adhesives are now becoming more and more common.



Extrusion pumps for low to high viscosity adhesives

(Source: WIWA)

9.2.2.3 Cyanoacrylates

Cyanoacrylates are one-part, room-temperature curing adhesives that harden very quickly in contact with moisture. They are available in viscosities ranging from water-thin liquids to thixotropic gels. When pressed into a thin film between two surfaces, the moisture present on the bonding causes the adhesive to form a rigid thermoplastic with excellent adhesion to most substrates. Typical fixture times are 5 to 30 seconds.

Cyanoacrylates are particularly suited for bonding aluminium to plastic parts and rubber. A bond between two aluminium surfaces takes longer to harden than a bond between aluminium and plastic or rubber materials. However, the peel and impact strength of cyanoacrylates is pretty poor, also their solvent resistance is relatively low. Thus, cyanoacrylates are not appropriate for the bonding of the metal parts in an automobile. The automobile-specific environmental conditions (exposure to moisture, temperature variations, solvents like gasoline or oil, salt spray, ultraviolet light, etc.) will lead to severe degradation of the bonded joint.

In addition to standard cyanoacrylates, there are many specialty formulations with somewhat enhanced performance properties. New two-part cyanoacrylates adhesives can provide larger gap filling capabilities, faster curing, and open/closed cavity cure potential.

9.2.2.4 Epoxy adhesives

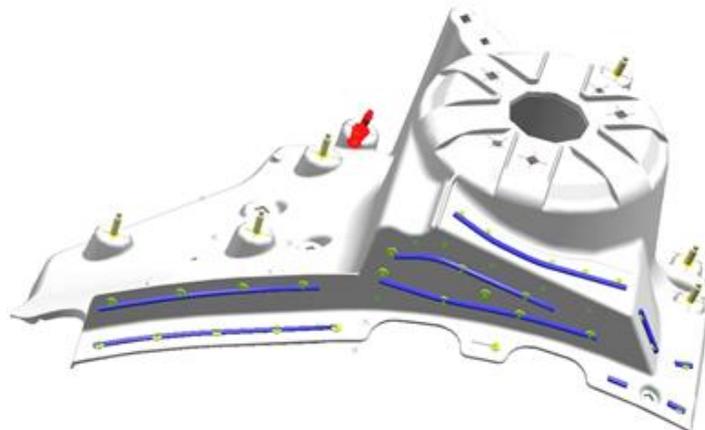
Epoxy adhesives consist of an epoxy resin plus a hardener. They are supplied as one and two-part systems with viscosities ranging from thin liquids that can be sprayed to thixotropic pastes which must be pumped. They have very good gap filling properties. Upon cure, epoxies typically form tough, rigid thermoset polymers with high adhesion to a wide variety of substrates and good environmental resistance. When exposed to elevated temperatures, epoxy adhesives may become rubbery, but cannot melt as a thermoplastic material would.

A big advantage of epoxy adhesives is that there are a wide variety of commercially available resins, hardeners and fillers. Thus the performance characteristics of epoxy adhesives can be tailored to the specific requirements of almost any application. Basically, there are two types of epoxy adhesives: Toughened (flexible) epoxies and glassy matrix (stiff) epoxies. Glassy matrix epoxies are extremely strong and rigid, and they resist shearing at very high force levels. Toughened epoxies are more flexible, but break under lower shearing forces and the bond is fairly heat-sensitive. Toughened epoxies contain a dispersed, physically separated, but chemically attached rubber phase which improves fracture and impact resistance. They are successfully used in many structural applications since they offer a suitable balance of toughness and durability. There are both stiff and elastic, two-component epoxy based adhesives.

When using a one-part heat-cure system, the resin and a latent hardener are supplied already in a mixed state and can have extended shelf life (storage) when refrigerated. By heating the system, the latent hardener is activated causing cure to initiate. The epoxy will normally start to cure rapidly in the temperature range 125 – 150 °C; curing temperatures of 150 °C and times of 30 to 60 minutes are typical. Heat curing also generally improves bond strengths, thermal resistance and chemical resistance.

When using a two-part system, the resin and hardener are packaged separately and are mixed just prior to use. This allows the use of more active hardeners, i.e. two-part epoxies will rapidly cure at ambient conditions. Two-part systems are normally mixed by passing them through a mix tip and dispensed as a single, homogenous liquid. However, two-component epoxy adhesives that cure at room temperature can rarely be loaded at temperatures above 80 °C. Epoxy adhesives with considerably higher heat resistance require heat curing, but also offer higher strength and improved durability.

Epoxy resins can accommodate significant addition of fillers, etc., without adversely affecting desired adhesion properties. Any single property (peel strength, shear strength, durability) can be improved by selecting an alternative chemistry, but usually to the detriment of the overall balance of properties. Formulating to meet specific application requirements provides epoxy adhesives with a wide range of properties that includes good chemical resistance, excellent adhesion, good mechanical properties, and little shrinkage, but also optimum cure and other processing conditions. In addition, epoxy adhesives can be formulated to be either conductive or insulating.



**Multi-material application rendering of epoxy adhesive on aluminium shock tower to steel rail
(Source: Henkel)**

9.2.2.5 Hot melt adhesives

Hot melt adhesives (“hot melts”) are mostly one-part, solvent-free mixtures of thermoplastics that are solid at room temperature. At dispensing temperatures (typically higher than 175 °C), they show low to medium viscosity and can be easily processed. After dispensing, hot melt adhesives cool and rapidly build up their internal strength allowing efficient assembly and further processing. But the high curing speed also has a drawback. When the hot adhesive meets a cold surface, setting is often so rapid that the adhesive does not properly wet the surface. The non-wetting effect is more distinct with increasing temperature difference between surface and adhesive as well as with increasing thermal conductivity of the substrate. Therefore, metals are sometimes heated before bonding with hot melts.

In the cured state, hot melt adhesives can vary in physical properties from soft, rubbery and very tacky to hard and rigid. Hot melts have excellent long term durability and resistance to moisture, chemicals, oils, and temperature variations. They are usually designed for light loads, only polyamides and polyesters can withstand limited loads at elevated temperatures without creep. Adhesion to plastics is good, but rather poor to metals since the thermoplastic hot-melt adhesives usually set too quickly.

The performance of the hot melt varies widely based on their chemistry:

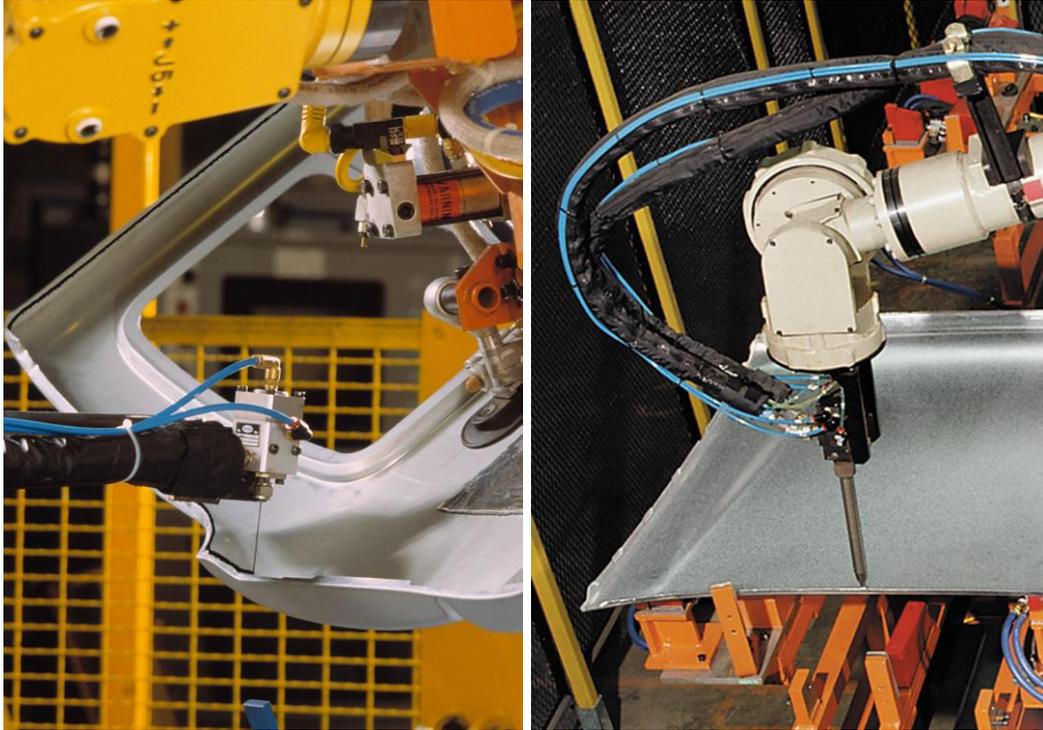
Ethylene vinyl acetate (EVA) hot melts are the “original” hot melt. They have good adhesive to many substrates, lowest cost, but typically have the poorest temperature resistance (upper service limit is about 50 °C).

Polyamide or polyester hot melts are higher cost, higher performing adhesives with good temperature resistance (up to 150° C), but long term strength at 70 – 80 °C is already quite low. The application temperature for this adhesives type is approx. 250 °C, i.e. a shielding gas must be generally used since at this temperature, the adhesive breaks down if it comes into contact with oxygen.

Polyolefin hot melts are specially formulated for high adhesion to plastics.

Because hot melts are based on thermoplastic polymers, they can be repeatedly heated to melt and cooled to solidify. Thus, they can be used to create bonded joints that are thermally detachable and can be re-attached later. However, this unique characteristic limits the temperature resistance of hot melt bonds and explains their tendency to creep when subjected to continuous stress or elevated temperatures. Many thermoplastic hot-melt adhesives also become brittle in cold environments.

Today, curing hot-melt adhesives are available too. These adhesives are based on polyurethanes that cure on contact with moisture. They are solid before the curing process actually starts. The application temperature of the polyurethane-based hot melts is considerably lower than for the thermoplastic hot-melt adhesives.



Application of hot melt adhesives

(Source: Nordson)

9.2.2.6 Polyurethane adhesives

Polyurethane adhesives are supplied as one and two-part systems which range in viscosity from self-levelling liquids to non-slumping pastes. They are made of urethane polymers with chemical based of isocyanate group. There are three different types of polyurethane adhesives:

- Two-component polyurethane adhesives
- One-component polyurethane adhesives curing by heat (rigid)
- One-component polyurethane adhesives curing by moisture (elastic).

Polyurethane adhesives are extremely versatile and can range in the cured form from highly elastic elastomers to rigid thermosets. The elastic polyurethane adhesives are cured by moisture whereas the rigid polyurethane adhesives are cured by heat input.

Single component systems typically consist of non-volatile urethane pre-polymers. The elastic variants are cured by polyaddition; moisture acts as the hardener. Since the cure is dependent on moisture diffusing through the polymer, curing is comparatively slow (hours) and the maximum depth of cure that can be achieved in a reasonable time is limited at approximately 10 mm. However, because the curing time mainly depends on the moisture concentration, curing can be accelerated through the addition of a product containing mostly water in a mixing nozzle, resulting in a homogeneous and fast cure. The curing temperature has only a small effect on the curing times and 70 °C is a practical upper limit. Moisture-curing polyurethane adhesives show an elongation to fracture of up to 600 %, but their strength level reaches only about 8 MPa.

In rigid one-component systems, temperatures in the range 100 °C – 200 °C are required to unlock the isocyanate groups necessary to produce the polyurethane. Heat curing results in a lower curing rate compared to that of polyurethane adhesives cured by moisture, but produces a highly cross-linked thermoset polymer with a strength of about 15 MPa, a maximum elongation to fracture over 20 % and high fatigue resistance. Innovative snap-cure one component hybrid polyurethane technologies are being introduced to facilitate shorter cycle times in assembly operations.

Two-component polyurethane adhesives can be elastic or rigid, depending on the structure the adhesive acquires once it has fully cured. For the resin, polyols with low molecular weight are used; for the hardener low molecular weight pre-polymers with isocyanate ends. After mixing the two components in the right proportions, the curing process of the adhesive starts immediately. The fast

cure usually means that the adhesive must be applied by machine. In case of the elastic variant (elastomer structure), the main advantage of the two-component system compared to the one-component variant is a very good creep resistance. The rigid two-component polyurethane adhesive (thermoset structure) offer an interesting combination of cohesive strength (about 25 MPa) and flexibility (maximum elongation to fracture over 50 %) that results in a good fracture toughness. A specific advantage is the minimal dependence of the adhesive properties over a service temperature range between approx. – 30 °C to + 80 °C. Some types of two component ambient cured polyurethane adhesive can be applied over some surface soils without need for pre-cleaning or oxide removal.

A preferred application of two-component polyurethane adhesives is structural bonding in the assembly area, i.e. after electro-coating and/or painting, in particular for the combination of dissimilar materials (e.g. metals to plastics and fibre reinforced composites) or pre-painted metal assemblies. This is due to the fact that there is no need for surface pre-treatment or external heating for curing. It is also possible to fill joints that have large gaps.

Initially, polyurethane adhesives were considered as possible replacements for epoxy adhesives for health and safety reasons. However, the risks of isocyanates means that they cannot be seen as a safer option than epoxies. When using epoxy, skin allergies are the greatest risk, for polyurethane adhesives, breathing difficulties dominate.

9.2.2.7 Elastomeric adhesives

Elastomeric adhesives, specifically silane modified polymers and silicones, are available in one-part moisture curing systems as well as two-part static mix systems that range in viscosity from self-levelling liquids to non-slumping pastes. On curing, they form soft thermoset elastomers with excellent thermal resistance. Silane modified polymers and silicones offer good adhesion to many substrates, but their applicability as structural adhesives is limited by the low cohesive strength. Elastomeric adhesives are typically cured via reaction with ambient humidity at room temperature, although formulations are also available which can be cured by heat, mixing of two components, or exposure to ultraviolet light.

Since the cure of moisture-curing elastomers is dependent on moisture diffusing through the elastomeric matrix, the cure rate is strongly affected by the ambient relative humidity and the maximum depth of cure is limited to about 10 mm. Complete curing depends on the film thickness and can take several days. This occurs because the reaction between the reactive groups on the polymer and the reactive groups on the substrate surface is slower than the crosslinking reaction of the products groups with themselves.

Silicones remain highly elastic at low temperatures (-75 °C), and also have very good temperature stability; up to 200 °C continuous exposure and up to 300 °C for short periods. The properties of silicones remain virtually unchanged over this temperature range. Silicones are nearly inert to chemicals and have excellent resistance to moisture and weathering. Bonds made with silicones can, however, only be subjected to relatively small mechanical loads. That is why they are chiefly used as sealants. They are used for bonding metal when the low bond strength is offset by the higher flexibility and resistance to low temperatures. Several types of moisture curing silicones are available depending on the bonding conditions and substrates.



Liquid gasket sealant adhesive robotically dispensed onto an aluminium cover

(Source: Henkel)

Two component silicone adhesives are available with a range of properties and cure rates. The initial strength and rate of strength build-up is typically higher than that of moisture cured silicones. The curing reaction can take up to 24 hours. Meter mix equipment is used to pump the two components through a mixing element. The mixed adhesive is then dispensed in bead form.

9.2.2.8 Anaerobic adhesives

Anaerobic adhesives are based on synthetic acrylic resins and only harden when in the presence of a metal and absence of oxygen. Anaerobic adhesives work by completely filling gaps between metal components. They are often termed locking compounds as they are used to secure, seal and retain close-fitting parts. Using an anaerobic adhesive augments the holding force of a mechanically joined assembly and prevents loosening under vibration and protects the joint from corrosion. They are typically used as thread lockers, thread sealants, flange sealants, etc.

Anaerobic adhesive are thermosets and provide high shear strength. They maintain their integrity at temperatures up to 200 °C. The bonded joints are, however, very brittle and are not suitable for flexible substrates. Curing occurs exclusively in the joined area and only relatively small gap widths can be bridged (maximum gap about 0.1 mm). Special formulations have been developed which provide improved overall performance under thermal and mechanical stress and are less surface-sensitive, i.e. which can be applied also on oily and contaminated surfaces. Besides their bonding function, anaerobically curing adhesives are often simultaneously used for their sealing properties because they are very resistant to oils, solvents and moisture. However, they cannot be used for bonding to plastics.

9.2.2.9 Plastisols

Plastisols are single-component adhesives that are applied as a paste consisting of solid polyvinylchloride (PVC) particles dispersed in a liquid plasticizer. In order to form a bond, the applied adhesive is heated so that the thermoplastic PVC swells and can take up the plasticizer. The two-phase system converts to a single-phase system by incorporating the plasticizer in the swollen polymer. This process occurs at a temperature between 150 and 180° C and results in an adhesive film consisting of a plasticized polymer. The cured product may be a soft, rubber-like material or a tough, hard solid.

Plastisols have high flexibility and good peel resistance. However, they are sensitive to shear stress and also tend to undergo creep when subjected to loads. For most applications, as an adhesive sealant this has no adverse effects. Being thermoplastics, they only have limited resistance to heat.

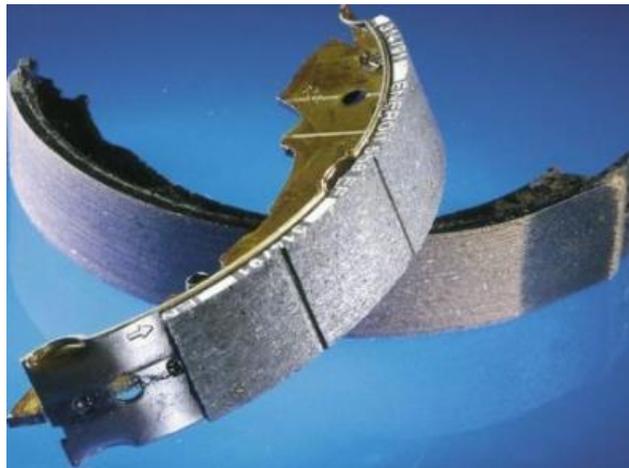
If overheated, for example during spot welding, there is also the risk of liberating hydrochloric acid. A typical area of application for plastisols is in vehicle body construction. Besides their bonding function, they also serve to seal joints against moisture, to dampen vibrations and to increase the rigidity of the body. Plastisols can also be used to bond non-pretreated metal sheets as they have the ability to take up oil. On the down side, PVC plastisols give rise to environmental problems when recycling the bonded components, and consequently have become increasingly replaced by alternative adhesives, such as epoxy resins.

9.2.2.10 Rubber adhesives

Based on solutions or latexes, rubber adhesives solidify through loss of solvent or water. Rubber is particularly suited as a bonding element because of its flexibility. In many situations, sealants must be able to expand and contract because they are sometimes used on parts that experience temperature variations. Styrene is one type of rubber adhesive commonly used in automobile manufacturing because it adapts well to temperature and pressure changes. However, they are not suitable for sustained load.

9.2.2.11 Modified phenolics

Phenol-formaldehyde adhesives cure at temperatures between 100 and 140° C depending on the composition of the adhesive. During the cure, water is liberated from the adhesive. As the curing process requires temperatures above 100° C, the liberated water is present in gaseous form. In order to avoid foaming, phenolic resins are cured under pressure. Pure phenolic resins are very brittle and sensitive to peel stress, thus modified phenolic resin adhesives which contain additives in order to increase the elasticity are generally used. They offer good mechanical properties and temperature stability. In the automobile, they are used for bonding brake and clutch lining materials.

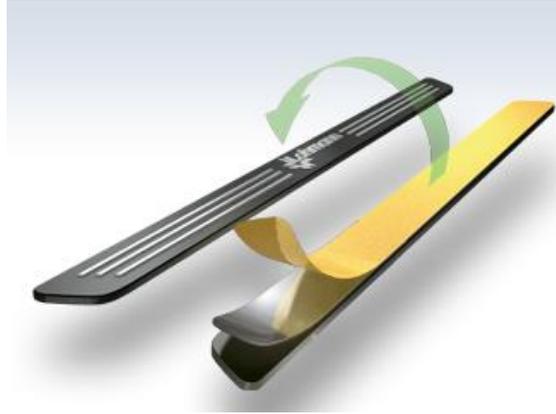


Brake linings are bonded using modified phenolics

(Source: www.adhesives.org)

9.2.2.12 Pressure-sensitive adhesives

The special feature of pressure sensitive adhesives is that they do not solidify to form a solid material, but remain viscous. As a result, they remain permanently tacky and have the ability to wet surfaces on contact. Bonds are made by bringing the adhesive film in contact with the substrate and applying pressure. If inadequate pressure is applied or the processing temperature is too low, bonding faults such as bubbles or detachment can occur. Since these adhesives are not true solids, the strength of pressure sensitive adhesives decreases when the temperature is increased. Pressure sensitive adhesives also exhibit a tendency to undergo creep when subjected to loads. They are typically formulated from natural rubber, certain synthetic rubbers, and polyacrylates. Pressure sensitive adhesives are often used to temporarily hold components in position during assembly.



Attachment of decorative trims with adhesive tapes

(Source: Lohmann)

Roof and decorative trims are often bonded to the vehicle using adhesive strips. On the one hand, the trim has to bond reliably at all temperatures and under all weather conditions. On the other hand, the adhesive tape must remain invisible for cosmetic reasons. The tape has to be adapted perfectly to the thermal expansion characteristics of the trim and the bodywork. As the trim usually expands more in heat and contracts more in cold weather than the metal or the plastic to which it is bonded, the tape must be able to compensate for these differences.

9.3 Adhesive application

Developments in robotics, control systems and metering, dispensing and monitoring equipment have made adhesive application a highly automated, controlled and repeatable process. However, various measures have to be taken in order to guarantee consistent, reliable high quality bonds.

Adhesives must be stored under correct conditions (one-part adhesives usually refrigerated) and should not be used after their expiration date. Also adhesive containers must be kept covered and free of contaminants. Temperature must be carefully controlled. Some warming can be useful to lower the viscosity during compounding, but care must be taken not to start a chemical reaction that might prematurely cure the adhesive. Mixing is generally achieved under vacuum to minimize air and moisture entrapment, neither of which would benefit an adhesive bond.

9.3.1 Application techniques

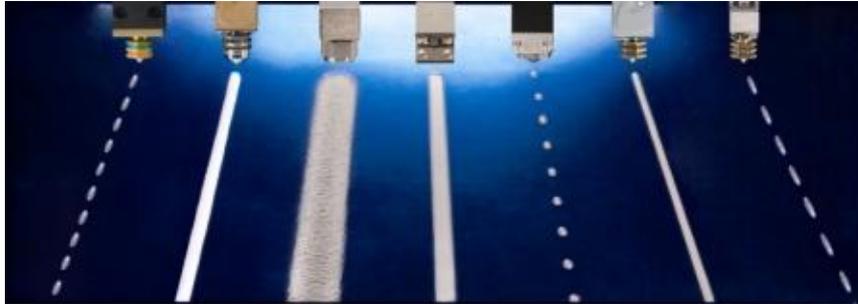
The possible application processes, depending on the consistency (solid or fluid) of the adhesive and on the application method used (manual or mechanised). Viscosity of the applied adhesive must be tailored to the application. Depending on the situation, the adhesive can for example maintain the bead shape until the force is applied to fill the bond line or it can flow into the bond line and fill any unevenness in the surface of the substrate.

In automotive manufacturing, automated application of adhesives is generally used. A wide range of equipment is available to apply virtually any adhesive or sealant during the manufacturing process. The optimum adhesive application method depends on the specific production requirements and the type of adhesive being used. Manual application is limited to repair bonding and the production of niche vehicles. Typical handgun systems can be cartridge-based or hose fed. Cartridge-based systems are portable, but require frequent refilling and costly cartridges. In addition, product quality strongly depends on operator skill. With selected nozzles for producing bead or spiral spray patterns, hose fed systems offer more consistent output than cartridge-based systems and optimize productivity.

Extremely short possessing times are attained through robot based adhesive bonding and seam sealing with appropriate adhesive application systems. The simplest method of robotic dispensing is extrusion. However, the extrusion method has now been largely replaced by the streaming and spraying technique which offers a significantly higher production rate. Automated guns offer a variety of options for achieving precise, consistent dot and bead patterns. Air-driven guns provide accurate timing and are insensitive to material viscosity and system pressure. Today's automatic pneumatic

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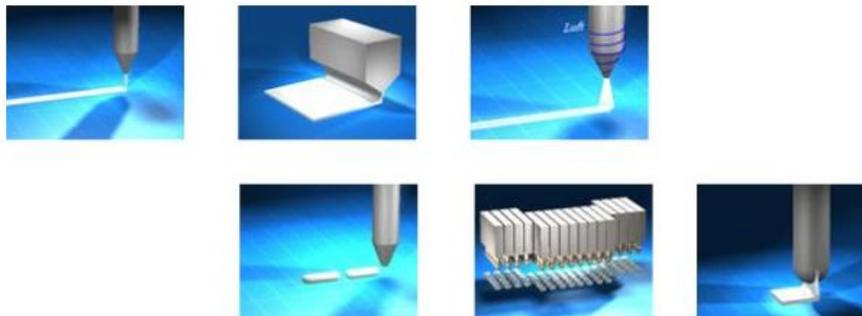
guns deliver reliable, long-life operation and can run at speeds that exceed 3500 cycles per minute. Also automatic electric guns can accommodate very fast cycle times. Typically incorporating an all-electric driver to optimize performance, these guns can achieve greater pattern control and consistency. In addition, by eliminating the used of compressed air and dynamic seals, automatic electric guns lower operating costs and minimize module maintenance.



Different dot and bead patterns

(Source: www.adhesives.org)

The small beam method is utilised to apply minute adhesive beads to the component, ensuring the same seam height and width. It is used for example in hem flange bonding. A constant width of the sealed seam can be consistently attained at high advance speeds by precisely controlled feeding of the adhesive. Depending on the specific requirements of the component, the quantity of the applied adhesive can be closely controlled. Adhesive bead diameters of less than 2 mm are possible. Finally, the quality of an adhesive bead determines the quality of the adhesive bond. Optical quality assurance devices can be integrated, because apart from the dosing system also the type of the feeding unit and the programmed robot track can have an influence on the produced adhesive bead.



Various application methods in the adhesive technology

(Source: Eisenmann)

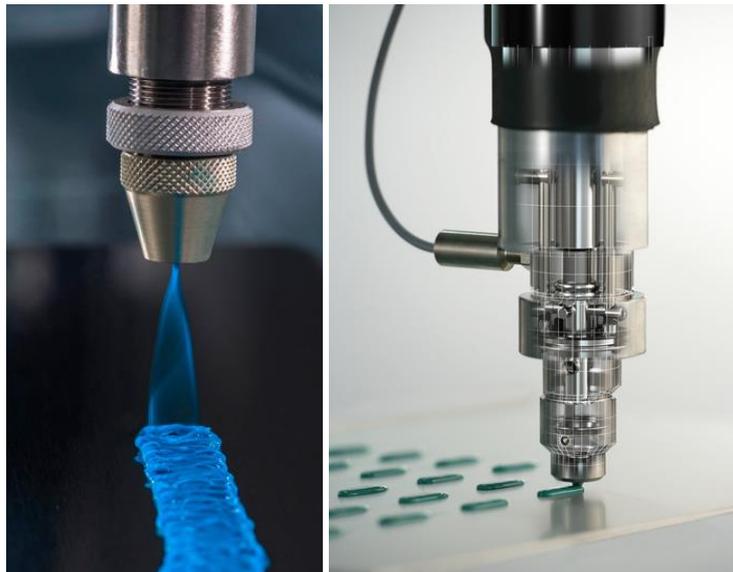
The wide slot application method enables dispensing of support adhesives or filler adhesives as well as silencing materials on large surfaces. The wide slot nozzles equipped with automatic low-wear high-pressure ball valves are available in dispensing widths up to 200 mm. This method is used in the automotive industry to apply dampening materials to components where no offset is allowed between the applied lengths. For this reason precision in series production is also indispensable in connection with the wide slot application method.

Further possibilities are the multipoint adhesive application method where the adhesive is applied at multiple points and the airless flat stream method. In the flat stream method, different dispensing patterns can be individually implemented using customized, single or multiple nozzles. Consequently, the flat stream method offers highest degree of flexibility.



Wide slot application method
(Source: intec Bielenberg)

In spiral spraying, large surfaces can be coated with adhesive in a single step and at high advance speeds. Reproducible spray patterns are created under full temperature control. The constant material flow enables rapid production processes. An interesting option is also the short bead technology which works with an electric servo drive allowing a much faster and more precise opening and closing of the applicator head than conventional needle valves and pneumatically operated pistols. The adhesive bead can be interrupted at precisely defined intervals for example when using a combination of spot welding and adhesive bonding. Adhesive-free sections can be attached with spot welds and without “burning” the glue. Thus the short bead technology improves the efficiency of the joining process both by saving adhesive material and reducing the cycle time in the body shop.



Spiral spraying (left) and short bead application technology (right)
(Source: intec Bielenberg/Dürr)

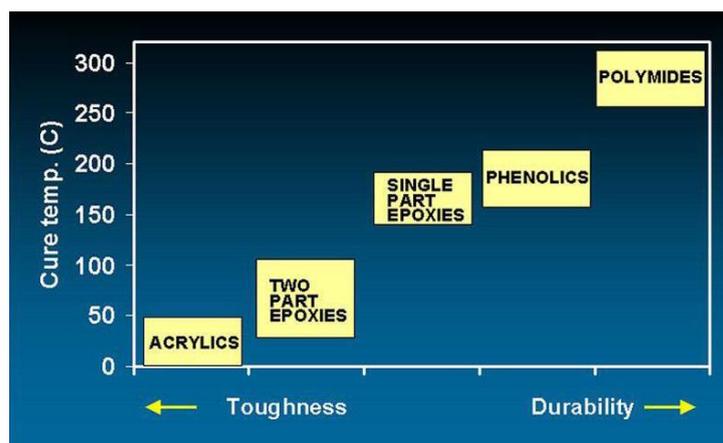
Bond line thickness is generally maintained through the tolerances of the manufacturing equipment, such as folding the sheet metal over to make a hem flange bond or moulding features into the bond area of a plastic panel. When manually preparing test samples, glass beads or wire of the appropriate diameter can be used to control the bond line thickness.

An important aspect is also proper environmental control of the area where adhesive bonding is performed (temperature, humidity, airborne contaminants, cleanliness, etc.). Also important is the correct handling of the parts to be joined, in particular any contamination of previously pre-treated surfaces must be prevented. In addition, it is necessary to anticipate any stresses (particularly peel

or cleavage) which may be encountered during assembly or handling. In specific cases, fixture or racks may be required to hold the assembly while the adhesive is curing.

9.3.2 Adhesive curing

Structural adhesives cure, generally with negligible contraction, in different ways. The applicable curing methods for the various types of adhesives have been outlined above. Generally, structural adhesive bonds in automotive manufacturing are cured by heating (although in some cases, pre-curing at ambient temperature takes place e.g. as a result of the mixing of two components or by contact with moisture). Cure is most often achieved with an oven cure, usually concurrent with the paint bake cycles in automotive applications. Curing by contact between hardener and adhesive and curing with UV light are relatively seldom used.



Curing temperatures for structural adhesives

As a rule, a higher cure temperature means more cross-linking and higher environmental resistance, but less toughness. Single part epoxies generally represent a good compromise with a wide range of properties, but they require curing at well over 100 °C. In case of two-component epoxy adhesives (where curing occurs already at room temperature), joints of a higher strength and improved durability can be achieved by curing at elevated temperatures. The curing times can be also considerably reduced as the curing time roughly halves for each 10 °C rise in temperature. Ultimate adhesion and mechanical properties are accomplished by extending the polymer chain and cross-linking between chains, with the cross-linking making the resultant polymer a thermoset. The reaction is often exothermic, releasing heat and furthering the cure. There are no by-products, i.e. potential outgassing issues are avoided.

9.4 Surface pre-treatment for adhesive bonding

Because adhesives bond to surfaces, the actual surface condition is most important. As a rule, the surfaces to be joined should be as clean and dry as practically possible. Surface pre-treatment will, therefore, normally be necessary if optimum performance of the adhesively bonded joint is aspired. Proper surface preparation generally improves both adhesive bonding and paint adhesion. On the other hand, alloy differences or even different materials are of less concern as long as the appropriate surface treatment methods are used and the applied adhesive bonds to both sides of the joint.

Surfaces are likely to be contaminated with materials that could adversely affect joint performance. Therefore, impurities (i.e. dust, dirt, oil, grease, fat or water) and the inactive adsorption layer created by foreign molecules (i.e. water and gases) are generally first removed. Care must be taken to avoid contaminating the surfaces during or after pre-treatment. Contamination may be caused for example by part handling (“finger marking”) or by other working processes taking place in the bonding area, e.g. oil vapours from machinery, metal dust from abrasive processes or vapours from spraying operations (paint, mould release agents, etc.).



Light truck entering multi-metal pre-treatment immersion stage
(Source: Henkel)

9.4.1 Aims of a surface pre-treatment

The main aims of a surface pre-treatment for adhesive bonding are:

- Removal of oil, greases and other contaminants as well as other surface layers, including weak oxide layers formed by heat treatment or exposure to humid atmosphere.
- Protect the substrate surface prior to bonding and maximise the degree of intimate molecular contact between the adhesive and the substrate surface.
- Generation of a stable surface topography for optimum mechanical interlocking.
- Improve durability and corrosion resistance of the adhesively bonded joint; promote formation of intrinsic adhesion forces that exhibit both resistance to environmental attack by moisture and chemical stability over a wide pH range.

The type and intensity of the surface treatment necessary for successful adhesive bonding depends on the materials to be bonded and the performance requirements of the bonded joint. It may include a simple surface cleaning step, a chemical conversion of the substrate surface, and/or the application of a suitable inorganic or organic coating.

In automotive manufacturing, however, a pressing lubricant is often present on the material surface when adhesive bonding takes place. Thus the adhesive must be able to absorb and displace this layer before wetting the metal surface. Due to the complex interactions of the adhesive and the adherent surface, and possible lubricant interactions, the adhesive cannot be selected in isolation. The adhesive, pre-treatment and lubricant must be chosen as a fully compatible system. In addition, pre-treatments employed in the automotive industry generally need to be simple and rapid in order to comply with the low cost and high manufacturing speeds required for automotive production. High performance aerospace pre-treatment techniques are clearly not appropriate for volume car production.

9.4.2 Surface pre-treatment of aluminium alloys

The surface treatment methods applicable for aluminium alloys are covered in detail in another section of the EAA Aluminium Automotive Manual (see **Manufacturing – 4 Surface Finishing**). In the following, only some aspects relevant to the adhesive bonding process will be reviewed shortly.

The aluminium surface is a complex transition zone between the bulk of the alloy and the environment (see 9.0.1). A thin (“natural”) aluminium oxide layer lies on top of a subsurface layer

with different chemical and microstructural properties than the bulk material. In rolled aluminium products, the disturbed (“deformed”) surface layer generally has a thickness of a few 100 nm. It contains rolled-in oxide particles from the high forces used during hot and cold rolling; it has elongated and smaller grains than the bulk and it can contain various intermetallic particles different in chemistry and concentration to the bulk.

The natural aluminium oxide film has a thickness of a 5 – 20 nm and follows exactly the material surface topography. In principle, this oxide film would present an ideal basis for adhesive bonding. In fact, a high initial joint strength can be often obtained without any pre-treatment or by a simple degreasing of the aluminium surface before adhesive bonding. But in order to maintain the integrity of bonded joints, in particular in humid environments, some form of surface pre-treatment is always necessary, specifically if the joints are subjected to tensile stresses.

The underlying reason is that the natural oxide film is not perfect. It may show thickness variations and exhibit defects such as pores and fine cracks; the aluminium oxide can be disturbed locally (e.g. where intermetallic particles are present in the adjacent aluminium metal) and it can contain surface contaminants (e.g. residues of rolling oils). Furthermore, depending on the thermal history (temperature and time), solute alloying and impurity elements can diffuse from the matrix into the surface oxide layer, modifying the structure and composition of the surface oxide film. Surface enrichment and the formation of a heterogeneous surface oxide layer is particularly pronounced for element like Mg, Li, Na, Be, and Ca. These effects degrade the characteristics of the surface oxide layer, i.e. make it more hygroscopic and less corrosion resistant. Therefore, the natural, inhomogeneous aluminium oxide surface film is often removed and replaced by a properly controlled, new, homogeneous surface film.

Depending of the specific aluminium product (sheet, extrusion, casting, etc.), the applied surface pre-treatments in preparation for adhesive bonding may be somewhat different; however, the individual steps are essentially the same. Rolled aluminium products are often already surface pre-treated in the mill in order to avoid chemical processes within the press shop or assembly plant. Other product forms are generally surface treated by the supplier and delivered ready-for-assembly.

9.4.2.1 Surface cleaning

Simple cleaning (“degreasing”) removes surface oils and contaminants. Cleaning approaches differ in aggressiveness depending on need. In some cases, detergent solutions may suffice. More aggressive cleaning (“deoxidizing”) requires an alkaline rinse, an acid rinse, or polyphenols followed by water rinsing. Deoxidizing only involves minimal metal removal. These cleaning methods are minimum practice in automobile applications. Proper degreasing provides a clean bonding surface which can be sufficient for moderately stressed joints in a dry environment. In general, however, degreasing is followed by additional surface treatment steps.

Mechanical cleaning approaches include surfacing techniques such as brushing, grinding, polishing, and sand or dry ice blasting. For many substrates, light abrasion of the surfaces to be bonded may allow a better interlock of the adhesive. However for aluminium, the application of abrasive methods is generally not recommended. If mechanical surfacing methods are applied, special care must be taken since the resulting deformed surface layer may severely impair corrosion resistance.

Although mechanical cleaning is not a commonly used process step in automotive manufacturing, mechanical surfacing methods are often used in rework and repair. If necessary, aluminium surfaces should be cleaned with a suitable abrasive cloth or water-proof abrasive paper. When using such techniques, operating under wet conditions can assist in the removal of contaminants and keeps dust generation to a minimum. If wet techniques are used, then the substrate must be thoroughly dried immediately after mechanical surfacing.

Fine grinding/blast cleaning removes weak surface layers and is therefore slightly safer than simple degreasing, but should be only used for stressed joints in dry environments. In specific cases, in particular for local adhesive bonding on painted surfaces, also laser cleaning may be applied. A further option is a surface activation step (such as plasma treatment).

The preferred surface cleaning option for aluminium is generally the alkaline or acidic cleaning/etching process which involves overt metal removal, in particular in preparation for subsequent surface pre-treatments that provide a properly controlled, stable surface oxide. Cleaning and etching may be two distinct steps, or may be combined into a single step. In case of rolled

THE ALUMINIUM AUTOMOTIVE MANUAL

aluminium products, the cleaning/etching step removes rolling oil residues, aluminium debris generated during rolling as well as the natural inhomogeneous oxide layer. After an alkaline cleaning step, an acidic cleaning step must be always carried out to remove any smut layer (brittle aluminium hydroxide). For the acidic cleaning step, sulphuric acid or a mixture of sulphuric and hydrofluoric acid is often used. Additionally, nitric, nitric/hydrofluoric and phosphoric acids can be used. Also, there are continuous treatment lines which use electrolytic cleaning in a phosphoric acid electrolyte.

For high quality adhesive bonding, the alkaline or acidic cleaning/etching step is followed by the controlled build-up of a new oxide layer (i.e. conversion coating or thin anodised film). The exposure of the freshly acidic etched (pickled) surface to boiling water produces a corrosion resistant, but only moderately strong oxide layer. Thus this surface treatment method should only be used for lightly stressed joints using flexible adhesives.

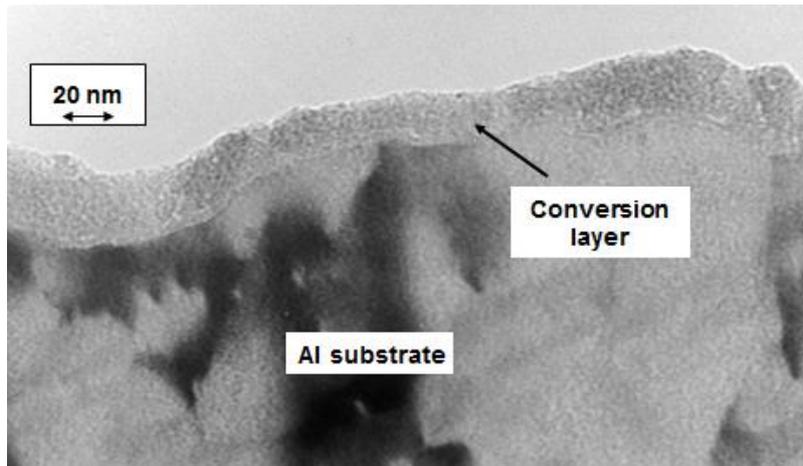
9.4.2.2 Conversion coating systems

Chemical conversion coating includes the dissolution of the natural oxide film and the controlled formation of a new, stable aluminium surface layer which reduces the risk of corrosion and improves the bonding of adhesives and/or organic coatings. The natural oxide film is removed by alkaline or acidic cleaning.

Traditionally, chromate films were formed on the aluminium surface. Conversion processes containing hexavalent Cr^{6+} ions perform exceptionally well for corrosion protection purposes because of their self-healing ability: when scratched or damaged, Cr(VI) reduces to Cr(III) and locally restores the film by forming chromium(III) oxide, thus healing possible weak spots. Cr(VI) is, however, a highly toxic and carcinogenic substance; its use is now being restricted for many applications by strict legislation. In response to the ban of Cr(VI) , Cr(III) processes were developed for some applications. Chromate layers offer good corrosion resistance, but their load bearing properties are relatively poor (i.e. for adhesive bonding, the chromate layer must be thin). This method works best for moderate loads and elastic adhesives. But for environmental reasons, Cr(III) -based conversion treatments are also not applied in the automotive industry.

Widely used in automotive applications are chromium-free conversion treatments based on either titanium fluoride or a mixture of titanium and zirconium fluoride (commercially offered for example by Henkel® or Chemetall®). The processing baths often contain organic acids or phosphate compounds to further improve adhesion. The surface pre-treatment is carried out either by conventional immersion, spray or no-rinse processes. During these types of chemical treatment, modified mixed oxide surface films containing titanium and zirconium ions are formed which are homogeneous, stable and offer good adhesion to organic compounds. Fluoride is necessary for the activation of the aluminium surface. The very thin conversion layers (10 – 30 nm) have no negative effects on the formability of the material; also material performance during welding or during the zinc-phosphating process (which normally precedes the final lacquering operation) is not influenced. Although the fluoride level in these conversion solutions is kept very low for health and safety reasons, its presence presents nevertheless a potential issue.

For this reason, other non-toxic alternatives have been developed. An early solution was PT2 (developed by Novelis). PT2 is a chrome- and fluor-free pre-treatment for structural adhesive bonding of aluminium sheet. It is applied on the strip surface as an aqueous suspension of colloidal silicate, with some additions required for film formation and wettability. The generated surface film follows exactly the strip surface topography and has a thickness of about 50 to 100 nm. Providing excellent long term stability of adhesive bonds, PT2 also offers good welding performance. The PT2 pre-treatment has been primarily developed for inner and structural sheet, it is not recommended for outer panel applications.



Ti/Zr-fluoride based conversion treatment (TEM micrograph of cross section through pre-treatment layer)

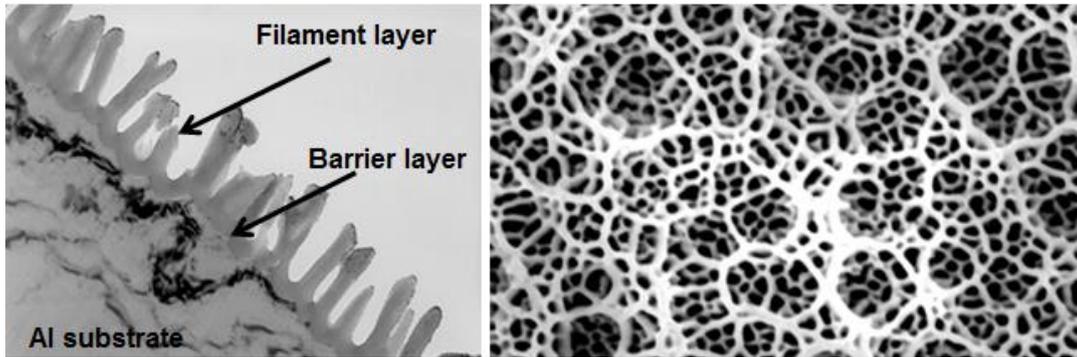
(Source: Novelis)

In addition, the use of silanes as adhesion promoters and for corrosion protection is widely investigated. Silanes are hybrid organic-inorganic molecules containing Si-O-C_nH_{2n+} groups which can interact with the metallic substrate to form a complex interface region containing -Si-O-M bonds (M=metal). After application, curing of the silane film is required to obtain a dense film network, which provides good corrosion barrier properties.

The newest development is the Alcoa 951 technology, an aluminium pre-treatment process that results in enhanced adhesive bonding durability compared with the conversion coating systems described above. The technology is applicable for aluminium sheets, extrusions and castings. It employs an organic, environmentally friendly system tailored for both the aluminium substrate and the structural adhesives used for joining. The surface treatment is applied through an immersion or spray application. The molecular structure chemically binds aluminium oxide with one end, and adhesive with the other. This creates a strong link at the molecular level resulting in lasting, durable joints for automotive structures. The minimal level of treatment on the surface offers full compatibility with downstream steps in the automotive manufacturing process such as forming, resistance spot welding and painting. In tandem with a suitably selected adhesive, the Alcoa 951 treatment is amenable to a variety of wet and dry film stamping lubricants.

9.4.2.3 Thin anodised films

In this case, a controlled film of active aluminium oxide, highly suited for structural bonding, is grown on the properly pre-treated aluminium (generally after electrolytic cleaning in an acidic bath); its thickness being dependent on the chemical process and the alloy used. Thin anodised films are generated using an AC or DC powered electrolytic process and have several advantages over conventional chemical cleaning and pre-treatment methods. They consist entirely of aluminium oxide and thus offer an environmental-friendly alternative to chromium or other transition metal based pre-treatments. In addition, the thickness and morphology of thin anodised films can be closely controlled by varying cell voltage and applied current. The formed oxide film consists of an amorphous barrier layer, which improves the corrosion resistance of the material, and a porous filament layer which provides excellent adhesion to adhesives, primers and lacquers. Thin anodized films can be tailored to ensure excellent long term stability of adhesive bonds. For structural bonding, a film thickness in the range of 80 to 120 nm is recommended with a barrier layer of 30 to 40 nm and a filament layer of 50 to 80 nm. Thin anodised films do not affect sheet formability, joining characteristics, surface appearance or corrosion resistance after painting. The films are compatible with wet and dry press lubricants. During a typical layer forming zinc phosphating treatment of the body-in-white, the thin anodised films are removed and a homogeneous zinc phosphate layer is formed.



Thin anodised film produced by anodising in phosphoric acid (cross section and surface view)

(Source: Novelis)

Suitable aluminium oxide films with an open structure are produced by anodising in phosphoric acid; the anodic oxide contains “bound” phosphate which will provide some degree of durability to the final adhesive joint. The resulting, very stable oxide film exhibits the optimum pre-treatment for highly stressed adhesively bonded joints in corrosive environments. The porous surface is ideal when used with low-viscosity adhesives and primers. Sulphuric acid anodising techniques can also be used to pre-treat aluminium alloy surfaces, but the resulting thicker oxide film leads to a lower adhesive strength and durability. Anodising with sulphuric acid is best used with elastic adhesives for lightly stressed joints in corrosive environments. Some improvement is possible by dipping the anodised components in a solution of phosphoric acid to dissolve part of the anodic oxide layer in order to reveal a more open structure more amenable to adhesive bonding.

For other performance criteria, e.g. for a spot-weldable substrate, much thinner < 30 nm barrier non-porous films have been shown to be more suitable. This is readily achievable as the anodising process is highly controllable, i.e. for any given electrolyte, the process relies solely on the selection of the correct electrical parameters.

9.4.2.4 Primer coating

Modern coil treatment lines allow the application of an organic coating, subsequent to a suitable chemical pre-treatment step which is required to ensure adequate primer adhesion and corrosion resistance. Both conductive and non-conductive primers are available. The use of non-conductive primers offers the possibility to save surface finishing process steps at the car producer. Conductive primers are of particular benefit for protection against galvanic corrosion in mixed metal constructions, i.e. aluminium and steel and/or galvanized steel. Other advantages of coated material include for example surface protection during transport and handling, improved formability as well as good adhesive bonding characteristics. However, there are also some disadvantages, e.g. welding of primer-coated aluminium sheet is not possible.

The main purpose of priming prior to the bonding of aluminium is to fill (seal) the surface when high-viscosity and/or fast setting adhesives are to be used. Priming becomes more important where the aluminium is to be used in a corrosive environment and no surface treatment that improves corrosion resistance (e.g. anodising) is considered.

9.4.2.5 The total system approach

As outlined above, care must be taken that the chosen adhesive is compatible with subsequent processing steps in car body manufacturing, in particular all the various operations in the lacquering line. However, the selected adhesive must be also able to comply with preceding processing steps. This aspect is most important for rolled aluminium products where various surface pre-treatment steps are often already carried out in the rolling mill. As a consequence, a holistic approach is necessary.

The Aluminium Vehicle Technology (AVT) concept for the production of aluminium car bodies developed by Novelis covers the selection of the appropriate sheet alloys, the surface cleaning and chemical surface treatment method, the application of a suitable lubricant and finally the choice of the proper structural adhesive. Depending on the customer requirements, either complete coils or cut blanks (rectangular or specific shapes) are supplied. The supply of aluminium blanks in any arbitrary geometry ("ready for stamping") produced on highly automated laser cutting lines in the rolling mill offers substantial cost reduction potential in particular for smaller production volumes (elimination of the blanking step, more effective process scrap handling and recycling, etc.).

In the AVT system, the aluminium sheet material is supplied by the aluminium manufacturer as a pre-treated and lubricated sheet. The car body panel is then stamped in the conventional way, without further application of lubricant. Only in specific cases, minimum additional local lubrication is required. The parts are joined by adhesive bonding (generally using a single part toughened structural epoxy adhesive) and locally supported by self-piercing riveting (or another secondary joining technique). The adhesive in the complete body structure is then cured during paint baking of the electro-coat layer. No cleaning or surface preparation is needed in the press shop and assembly plant.

A key element of this approach is the lubricant on the sheet surface. Different kinds of lubricants can be applied. Normally, only a thin lubricant film is applied to protect the material surface against corrosion and friction effects. In the press shop, this film is then replaced by a proper press forming lubricant. In principle, it would be possible to directly apply a lubricating oil that can be used for forming, eliminating the need to apply additional lubrication at the press shop. However, the oil can redistribute during transport and storage resulting in an inhomogeneous distribution.

The preferred approach is therefore the application of a dry lubricant film suitable for press forming in the rolling mill. Depending on the complexity of the panel to be formed, typical coating weights are in the range of 0.5 to 1.2 g/m². The trend is to use mineral oil based dry lubricants that are applicable for both aluminium and steel sheet. The lubricants are applied at temperatures of about 60 to 70 °C, and solidify at about 50 °C. In general, the dry lubricants are not removed from the stamped panels. Consequently, the applied dry lubricants must be compatible with any adhesives applied during assembly as well as with all the agents used in the sprays and immersion tanks during zinc phosphating and electro-coating. In practice, the lubricant is removed from the assembled body-in-white only in the alkaline degreasing step immediately before zinc phosphating. But even if the body-in-white is thoroughly degreased, traces of lubricant might still be present (e.g. in crevices) and could be transferred into the electro-coat bath. If the applied lubricant is not fully compatible with the electro-coat process, craters or pimples could develop on the lacquered surface which would lead to costly rework.

A disadvantage is that up to now, no dry lubricants are available which allow high quality fusion welding of the lubricated material. Without a pre-cleaning step, weld porosity will generally be observed when dry lubricated sheets are fusion welded.

9.5 Properties of adhesively bonded aluminium alloys

Joint design incorporating adhesives requires specific attention because of the large property differences between the adhesive and the materials being bonded. In order to correctly understand the effect of different adhesives on a bonded joint, the bonded joint must be considered as an independent structural element in a composite structure. It has different mechanical properties which can be influenced in a different manner by temperature and other environmental conditions. Since the durability of the various adhesives in different environments is generally known, the selection of an appropriate adhesive presents normally little problems.

Low-strength bonded aluminium joints are often a boundary layer problem, i.e. the result of undesired effects between adhesive and aluminium oxide. Water, either in its liquid or vapour phase, is the most common and generally most severe environmental stress factor. Different adhesives can differently interact with the aluminium surface in the boundary layer as a result of the electrolytes that can form in the presence of water. The effect on the boundary layer is even more negative if the water contains salts.

The long-term strength of a bonded aluminium joint exposed to moisture depends on the quality of the connection between the adhesive and the aluminium surface (e.g. water can penetrate into incompletely filled surface roughness's) and the stability and durability of the existing surface oxides

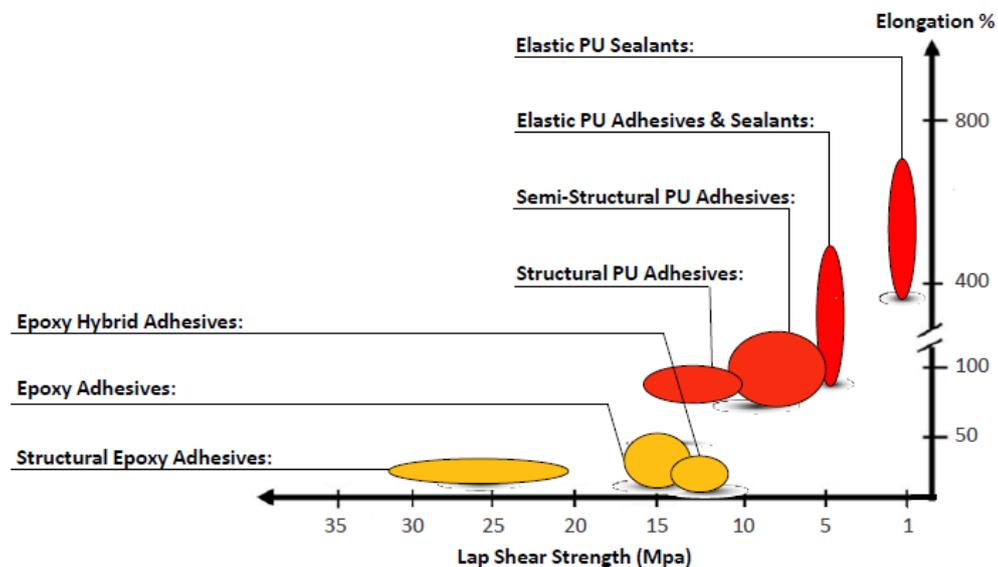
in the presence of the water (or a salt-containing electrolyte). Bonding to a naturally formed aluminium oxide surface layer does not provide the required long-term strength. If there is water or high air humidity in the service environment, the natural surface oxide must be replaced by a stable oxide layer formed under carefully controlled conditions to increase the durability of the bonded joint.

In addition, during any assembly operation, there is always the possibility that no adhesive is dispensed over a certain flange length/area (e.g. due to problems with the adhesive dispensing equipment). This will result in local loss of joint strength. Experimental work showed that the reduction in strength is directly proportional to the length of the adhesive skip. A small skip will generally only result in a small reduction in joint strength (assuming joints are loaded uniformly). In real structures, however, joints are often non-uniformly loaded and the position of the skip will be as important as its size.

9.5.1 Mechanical and thermal properties of adhesives

Detailed information about the inherent bulk mechanical and thermal properties of the adhesives is generally available from the respective suppliers. But the bulk mechanical properties of adhesives do not quite represent the strength performance of a bonded joint. Nevertheless, the bulk properties are still important parameters. Structural adhesives suitable for aluminium have an inherent bulk tensile strength of 10 to 60 MPa and an elastic modulus of 1 to 5 GPa.

The shear strength of a good adhesive bond on aluminium reaches approximately 30 MPa, even if the bulk tensile strength of the adhesive material reported in the technical data sheet may be 40–50 MPa. High-strength aluminium alloys for automotive applications have yield strength level approaching 300 MPa and an elastic modulus of approximately 70 GPa. The elastic modulus for steels and fibre reinforced composites is significantly higher. Consequently, the adhesive mechanical properties will always be lower than those of the materials being bonded together. Thus, it is reasonable to assume that an adhesive bond on aluminium can (and should) fail internally in the adhesive itself (“cohesive failure”).



Lap shear strength of bonded aluminium joints

(Source: Dow)

The coefficient of thermal expansion for most adhesives is slightly higher (30 – 40 ppm/°C) than that of aluminium alloys (approx. 20 – 25 ppm/°C). Because the adhesive has a lower elastic modulus, this mismatch is generally manageable. However, the mismatch is about triple that for steel (12 ppm/°C) and double that for carbon fibre reinforced composites (10 – 20 ppm/°C). Thus, in mixed material joint design, it is important to allow for thermal strain effects. The joint will fail if thermal strain exceeds the bond shear strength. Similarly, residual strain or any other added strain in combination with the operating load must be compensated in joint design.

The properties of an adhesive are strongly temperature dependent. The elastic modulus of an adhesive decreases with increasing temperature. At some point, the adhesive ceases to be visco-elastic and deforms plastically. Therefore, when stressed by further heating or mechanical loads, the resulting strain leads to permanent deformation. The temperature at which permanent deformation occurs is called the glass transition temperature. For a structural joint to be thermally stable, it is best to select an adhesive with a glass transition temperature that is 10 °C – 15 °C higher than the highest expected operating temperature.

For many adhesives, the maximum temperature at which stressed bonded joints can be used in practice is between 60 and 80 °C. The highest heat resistance (approx. 150 – 250 °C) is achieved with heat-curing adhesives. Silicon adhesives can also provide a heat resistance of about 250 °C without heat curing.

Most critical are the reduced creep resistance of adhesives at high temperatures and an increased sensitivity to stress concentrations and shock loads at low temperatures. Different adhesives, even within the same group, can be affected to a different degree by temperature. When bonded joints are to be exposed to long-term tensile loads at elevated temperatures, application-specific tests will be often necessary to ensure that the creep strength of the applied adhesive meets the requirements.

9.5.2 Performance of adhesively bonded joints

In order to design a component or structure with adhesives, it is essential to have confidence that an adequate joint strength and performance will survive throughout the lifetime of the vehicle. The mechanical performance of adhesively bonded joints differs widely. It depends on the actual bond strength, the joint design, and the environmental exposure conditions. There are many different standardized test methods, e.g. to determine the lap shear strength of bonded joints or the peel resistance of adhesives. Apart from a suitably durable adhesive, it is essential that the substrate and interface do not fail during the vehicle life.

Specific shear strength data for adhesively bonded joints are available from the adhesive suppliers. Typically, bond strengths are evaluated at ambient conditions and after exposure to high temperatures as well as high humidity and corrosive environments. Sometimes, also the effect of the surface roughness of the substrate has been evaluated.

On the other hand, there are no completely non-destructive methods for testing adhesively bonded joints. Non-destructive tests allow the measurement of pores, non-uniform adhesive layer thickness and absolute joining defects; however, the quality of adhesion cannot be determined. Normally, specially prepared test samples which run through the standard manufacturing process are used to control the adhesive joining process.

Bonded joints are normally regarded as rather insensitive to vibration and fatigue at high frequencies. They are often used as vibration dampers. Nonetheless, mechanical loads and specific environmental conditions can exacerbate boundary layer problems. The simultaneous effects of temperature, environment and mechanical load may result in a significantly faster strength reduction than would occur if these three stresses operated individually and had their outcomes added together. The stress concentrations that can arise when an adhesively bonded structure is loaded manifest themselves at the edges of the joints (especially if the joint has not been designed to minimize such concentrations), where environmental impact is also greatest. This can result in more rapid aging of the bonded joint than would otherwise have been the case.

9.5.3 Long-term durability

The most important environmental factors determining the durability of adhesive bonded aluminium joints are humidity, temperature and mechanical stress. Normally, moderately increased temperatures or mechanical stresses have no adverse effect on a structural joint. However, in the presence of water, increased temperatures may lead to accelerated degradation. Apparently, increased diffusion of water into the adhesive is an important factor. The rate of joint degradation by water is further increased if the joint is subjected to stress. Cyclic loading seems to be more detrimental than a constant load.

Under standard environmental conditions, there is normally no problem with respect to degradation of the adhesive or failure of adhesion. However, adhesively bonded joints are often located in

confined zones where water and salt can accumulate for longer times. Thus the micro-environment in these confined zones is usually much different from the open (outdoor) atmospheric conditions.

9.5.3.1 Effect of moisture on a bonded joint

Water (often in the form of salt water) is the predominant factor in bond degradation. Water can enter the bonded system by bulk diffusion through the adhesive, interfacial diffusion along the interface between the adhesive and substrate, and by capillary action through cracks or defects in the adhesive or conversion layer. Absorption of water may slowly plasticize and weaken the adhesive, i.e. lower the glass transition temperature of the adhesive and decrease the load bearing capacity of the joint. Water may also displace the adhesive at the interface and cause true interfacial failure. Furthermore, the presence of water may cause chemical degradation of the adherent interface by corrosion of the metal (in particular in the presence of salt). Hydrolysis can also lead to weakening of the oxide layer covering the aluminium substrate. The aluminium oxides produced by the applied surface pre-treatments are often not thermodynamically stable in a humid environment and may react with water to form hydrated oxides. All these effects will intensify with increasing temperature and humidity.

But there are also additional factors. Since the aluminium surface is never completely flat, highly viscous (slow flowing) and fast setting adhesives will most probably only come into limited contact with the surface. This results in a bond with in-built weak points (air pockets). In humid environments, the air will eventually be replaced by (salty) water.

Furthermore, the type of the applied adhesive may influence the stability of the interfacial region as a result of chemical reactions between water and specific components of the adhesive, thus forming products that leach out and can react with aluminium oxide. Specifically, it is assumed that an alkaline environment is formed in epoxies by reactions between water and curing agents such as dicyandiamide, causing attack of the aluminium oxide. In contrast, residues leaching from phenolic based adhesives are slightly acidic, which possibly contributes to the superior joint durability often shown by phenolic based adhesives.

9.5.3.2 Test methods for evaluating adhesive bond durability

For a structural joint, load and ability to withstand creep under extreme conditions are most important. In practice, long term performance of bonded joints cannot be reliably predicted from the properties of the adhesive and the adherent surfaces. Bond lifetime depends on the synergistic effects of stress, temperature and environment. The complexity of the interfacial chemistry generally requires experimental testing of the bonded structures. Hence, structural joints are usually exposed to severe testing conditions including variations of temperature and moisture, often with addition of salt for corrosion and some form of load.

Weathering tests of adhesively bonded aluminium generally include outdoor exposure (in case of automotive applications usually field tests under extreme climatic conditions) or accelerated testing under aggressive laboratory conditions. Although the conditions encountered in actual driving tests are close to service conditions, this type of testing is time consuming and requires several years before an evaluation of the bond durability can be made. The main difficulty is that in field tests – even at locations with extreme climatic conditions – rather static environmental conditions are encountered (e.g. relative humidity and temperature change slowly and within a rather limited range).

Therefore many efforts have been made to develop short-term laboratory test procedures which allow to draw safe conclusions concerning the long-term stability of adhesively bonded joints. Vehicle testing showed that environmental parameters such as dirt and mud have a significant influence. Fairly good correlation was obtained when using accelerated laboratory tests including cyclic temperature and humidity conditions and salt additions. Although it is difficult to use results from these tests to predict real life durability, a pre-treatment / adhesive system that performs well in accelerated tests provides a good starting point for the design and manufacture of bonded joints.

There is no harmonised specimen geometry and test procedure to evaluate adhesive bond durability in accelerated tests. Different conditions are used by the different car manufacturers and also by the suppliers. The test conditions used by car manufacturers often result from their experience with steel sheet. In addition, quite aggressive test conditions are applied during corrosive exposure in order to enhance the testing process and to allow a clear discrimination of different bonding systems.

THE ALUMINIUM AUTOMOTIVE MANUAL

Usually tensile lap shear tests are used for screening. Sometimes also wedge tests are carried out, although in this case, the preparation of the test samples is more complicated. Following the screening trials in the laboratory, actual driving tests are carried out at the car companies to evaluate the performance of the joined components under severe service conditions.

In laboratory testing, the geometry of the test specimen plays an important role. The use of a small sample width (or the introduction of drilled holes in the joint area) results in a stronger edge effect, i.e. it leads to a higher sensitivity regarding corrosive undermining effects compared to samples with higher width. Also pre-straining of bonded samples before corrosive exposure (e.g. 10 sec at 50 % of initial lap shear strength) should be considered. Pre-straining is used to simulate loading during service and may introduce micro cracks at the bond interface which are expected to increase corrosion sensitivity. An important parameter is the surface condition of the specimen before corrosive exposure. The use of plain test specimens results in most severe conditions as corrosive undermining can easily propagate from the plain edges. More realistic testing conditions are seen for samples with a zinc phosphate and electro-coat layer or even for samples with a zinc phosphate layer and a full lacquer system.

In general, the adhesively bonded samples for accelerated corrosion testing are aged in a cyclic environment including temperature and humidity; also important is the chloride concentration. In addition, a load is sometimes also applied. The samples are then evaluated based on both strength retention and failure mode. Typical tests applied in practice are the VDA Cycle Test (VDA 621-415 standard) or the Salt Spray Test (DIN 50021, ASTM B117). But there are also additional OEM-specific test procedures, e.g. the SCAB test defined by General Motors, the Climate Cycle Corrosion test (used by Audi/VW), the APGE test of Ford or the KWT test used by Daimler. More often a combination of different accelerated laboratory test methods is used in practice.