Disclaimer
The information is submitted as a suggestion for consideration. Norsk Hydro ASA, its divisions and subsidiaries ("Hydro"), do not accept any liability for any direct or indirect loss caused by or linked with the information contained in this document. Any proposed use of this information requires thorough testing and approval by the recipient before use. No warranties by Hydro, expressed or implied, accompany this information.
Production: Hydro Extrusions AS, Artbox AS, lg.linden/text

www.hydro.com
Adhesive Bonding of Aluminium Handbook
### Contents

1. **Product realization process**  
   1.1 Bonding system  
   2. Advantages and disadvantages  
2. **Aluminium**  
   3.1 Aluminium oxide  
   3.2 Alloying elements that affect corrosion  
   3.3 Surface layers  
   3.4 Extrusions  
   3.5 Rolled material  
   3.6 Castings  
3. **Requirements for adhesive bonding**  
   4.1 Adhesion, wetting and flow properties  
   4.2 Cleanliness  
   4.3 Wet adhesion  
   4.4 Pre-treatment  
4. **Properties of adhesive joints**  
   5.1 Failure modes  
   5.2 Mode of loading  
   5.3 Mechanical performance  
   5.4 Structural adhesive bonding  
   5.5 Elastic adhesive bonding  
   5.6 Joint design  
   5.7 Factors that have an impact on joint quality  
5. **Groups of adhesives**  
   6.1 Curing adhesives  
   6.2 Epoxy adhesives  
   6.3 Drying adhesives  
   6.4 Hot-melt adhesives  
   6.5 Adhesive tape  
   6.6 Designed and modified adhesives  
6. **Choosing an adhesive system**  
   7.1 Technical specification and requirements  
   7.2 Product properties  
   7.3 Process properties  
7. **Testing and verification**  
   8.1 Qualification  
   8.2 Quality assurance  
   8.3 Modeling of adhesive joints  
8. **Multimaterials**  
   9.1 Geometry and design  
   9.2 Composite material  
9. **Occupational health and safety**  
   10.1 Health issues in production  
   10.2 Surface treatment chemicals and primers  
10. **Appendix – Example checklist**  

---

1. Product realization process 6  
1.1 Bonding system 7  
2. Advantages and disadvantages 10  
3. Aluminium 12  
3.1 Aluminium oxide 13  
3.2 Alloying elements that affect corrosion 13  
3.3 Surface layers 13  
3.4 Extrusions 14  
3.5 Rolled material 15  
3.6 Castings 15  
4. Requirements for adhesive bonding 16  
4.1 Adhesion, wetting and flow properties 17  
4.2 Cleanliness 18  
4.3 Wet adhesion 18  
4.4 Pre-treatment 19  
5. Properties of adhesive joints 24  
5.1 Failure modes 25  
5.2 Mode of loading 25  
5.3 Mechanical performance 27  
5.4 Structural adhesive bonding 27  
5.5 Elastic adhesive bonding 28  
5.6 Joint design 29  
5.7 Factors that have an impact on joint quality 33  
6. Groups of adhesives 38  
6.1 Curing adhesives 39  
6.2 Epoxy adhesives 39  
6.3 Drying adhesives 43  
6.4 Hot-melt adhesives 43  
6.5 Adhesive tape 44  
6.6 Designed and modified adhesives 45  
7. Choosing an adhesive system 46  
7.1 Technical specification and requirements 47  
7.2 Product properties 47  
7.3 Process properties 48  
8. Testing and verification 50  
8.1 Qualification 51  
8.2 Quality assurance 51  
8.3 Modeling of adhesive joints 51  
9. Multimaterials 54  
9.1 Geometry and design 55  
9.2 Composite material 55  
10. Occupational health and safety 56  
10.1 Health issues in production 57  
10.2 Surface treatment chemicals and primers 59  
Appendix – Example checklist 60
Introduction

Future products have requirements for better performance, integration of functions and lower weight, without a cost penalty. This leads to a greater need for methods for joining different materials, where each material is selected based on its unique properties. Adhesive bonding is a joining method that offers possibilities to join basically all kinds of materials in different product categories.

With this publication, we wish to contribute to greater awareness of the possibilities and limitations that exist when it comes to adhesive bonding of aluminium. Our aim is to assist you in finding the best solution to adhesive-bonding requirements.
1. Product realization process

Joining is an important part of product development. Adhesive bonding is a joining method that can result in high-performance joints when aluminium is joined to aluminium as well as to other materials.

When a designer chooses adhesive bonding as the joining method, it is not only a specific adhesive that is selected, but a whole adhesive system (see Figure 1). This includes mechanical properties, surface treatment, mechanism of cure, application technique, joint configuration, quality assurance, corrosion properties, HSE aspects, etc. The whole system has to be considered when specifying requirements for functionality and properties.
1.1 Bonding system

Ideally, the product realization process can be divided into a concept development loop and a product development loop (Figure 2, on the following page).

The concept development loop involves an assessment of whether the planned product is able to meet the requirements of function, properties, customer expectation, choice of material, suitable manufacturing process, laws and public authority requirements, and whether the cost of utilizing the product is acceptable. Usually, different joining solutions are compared in the assessment.

Before the actual product development can start, it is essential that all requirements and requests are turned into a technical specification and that the various concept solutions, which adhesive bonding is part of, are thoroughly investigated and assessed by a multi-disciplinary team. This applies regardless of how basic or advanced the product concept is. The adhesive system will usually be a compromise between different requirements. Without technical specifications, there is a risk that the focus will shift from the most important requirement and lead to an unfavorable choice of adhesive system as result.

To verify that an adhesive system works throughout all production steps and the intended field service, extensive and time-consuming work may be needed. A lot of test results and experience with the adhesive system must be gathered before realization and dimensioning of the product (many tests may already have been conducted by the adhesive supplier). This means the choice often falls to systems that you have worked with previously in similar products and applications, or which are recommended to you.

As the properties of adhesives are rarely defined in a standardized way, it may be difficult to find the most appropriate adhesive systems for the task, especially since there are more than a quarter of a million different adhesive products on the world market. Consultation with adhesive suppliers based on the technical specifications can be helpful during the development process.

Don't underestimate the importance of creating a good technical specification for the joint/bonding.
1. Product realization process

Figure 2: A schematic description of the product realization process
PLM = Product Lifecycle Management
LCC = Life Cycle Cost
LCA = Life Cycle Analysis
Robotic adhesive application for an aluminum profile bonded to formed aluminum sheet. The end product is used in the commercial transportation industry.
2. Advantages and disadvantages

Adhesive bonding differs from soldering, brazing and fusion welding – perhaps first and foremost because the additive that creates the joint is made of plastic/polymer rather than molten metal. This permits the joining of different types of materials that could not otherwise be reliably joined. For example, welding and soldering do not work when joining metal to plastics.

Since heating a material (as in soldering, brazing and fusion welding) can reduce strength and cause deformation, the low or moderate temperatures involved in adhesive bonding have further advantages.

Compared to “spot” mechanical joints such as rivets, clinches and screws, which can have relatively high local stress, an adhesive joint can carry load over larger areas. The strength, stiffness, energy absorption and durability of a correctly dimensioned adhesive joint will therefore be better. Uniform load distribution can also enable a reduction in material dimensions. In general, the advantages of adhesive bonding become more apparent when joining thin materials.
<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Different materials can be combined</td>
<td>− Sensitive to peel and cleavage</td>
</tr>
<tr>
<td>+ Wider choice of construction materials</td>
<td>− Need for surface treatment to ensure cleanliness, wetting, adhesion and corrosion resistance</td>
</tr>
<tr>
<td>+ The joint is continuous</td>
<td>− Need for fixation during curing, limited handling possibilities</td>
</tr>
<tr>
<td>+ Uniform stress distribution without local “hot spots”</td>
<td>− High-temperature properties can be a limitation</td>
</tr>
<tr>
<td>+ Single-sided access</td>
<td>− Difficult to quality assure, rigorous process control required</td>
</tr>
<tr>
<td>+ Strong, stiff and impact-resistant designs</td>
<td>− The dosage and precision during application can be demanding</td>
</tr>
<tr>
<td>+ Good fatigue properties</td>
<td>− Health, Environment and Safety (especially for curing adhesives)</td>
</tr>
<tr>
<td>+ Long life</td>
<td>− Disassembly and reparation can be difficult</td>
</tr>
<tr>
<td>+ Details with large differences in dimensions can be joined</td>
<td>− Need for education in production and in service and maintenance</td>
</tr>
<tr>
<td>+ Sealing and joining in one step</td>
<td></td>
</tr>
<tr>
<td>+ Clean finish without the need to make holes</td>
<td></td>
</tr>
<tr>
<td>+ Reduces corrosion by filling crevices and ensuring galvanic separation</td>
<td></td>
</tr>
<tr>
<td>+ Can be performed at room temperature, different curing possibilities</td>
<td></td>
</tr>
<tr>
<td>+ Noise and vibration damping</td>
<td></td>
</tr>
<tr>
<td>+ Can be combined with other joining methods</td>
<td></td>
</tr>
<tr>
<td>+ Easy to automate the production flow with relatively low investment cost</td>
<td></td>
</tr>
<tr>
<td>+ Zero or limited heat impact on the material during joining</td>
<td></td>
</tr>
</tbody>
</table>
3. Aluminium

Aluminium is available in a variety of alloys and forms, depending on how the material has been processed (e.g. rolled, cast or extruded) and how the material has been heat treated.

Aluminium is a base metal and it immediately oxidizes when it comes into contact with air. From a chemical point of view the formed oxide layer is more stable than aluminium itself and this is the key to the corrosion resistance of aluminium. In many applications with low requirements on visual appearance the natural oxide offers corrosion protection that is good enough.

If the aluminium is to be painted or adhesively bonded and used in a corrosive environment, the natural oxide is too poor to ensure the required service life. Pre-treatment is necessary in order to produce a more stable and well-defined surface. It is important to remember that adhesives (as well as paint) never bind directly to aluminium but to oxides or conversion layers. The quality of these layers has a huge influence on the strength and corrosion properties of the joint.
3.1 Aluminium oxide

Aluminium oxide layers can consist of different forms of oxides and hydroxides. The composition depends on the circumstances during formation and the alloying elements and contaminants that are present. If water is present when the oxide is formed, it can also contain various proportions of crystal water. The composition affects the stability of the oxide. Usually, aluminium oxide is stable in the pH range 4 to 9. Below and above these limits, the risk of corrosion attack is much higher. This also means that both acidic and alkaline solutions can be used to etch aluminium surfaces during pre-treatment.

3.2 Alloying elements that affect corrosion

Apart from the oxide's protective properties, the corrosion properties of an aluminium alloy are controlled by the amount of more noble intermetallic particles in the material. If an electrolyte solution (water and salt) is present, corrosion can be initiated and the particles that are more noble than aluminium will act as cathodes while the surrounding areas will become anodes, where the aluminium dissolves.

Even particles that only contain small amounts of noble elements may quickly act as pure noble particles because of selective dissolution of aluminium on the particle's surface. Particles that contain iron cause a significant reduction in corrosion resistance, and copper is also known to reduce corrosion resistance. Higher concentrations of impurities, such as lead, at the grain boundaries, have a negative effect on corrosion resistance.

Alloys from the 5000 and 6000 series have relatively low levels of alloying elements and intermetallic particles, which make them relatively resistant to corrosion. In general, high-strength alloys contain larger amounts of alloying elements, which in turn results in reduced resistance to corrosion.

3.3 Surface layers

The surface layer of aluminium usually has different properties relative to the bulk material. The oxide layer has already been mentioned. Another important characteristic of the surface is that the concentrations of alloying elements and contaminants differ from the bulk of the material, and the metallurgical structure may also be different. This is a result of processing that involves elevated temperatures and mechanical shearing of the material, for instance extrusion, rolling, ageing and grinding. Changes that may occur at the surface include diffusion of certain elements toward the surface, accumulation of intermetallic particles in grain boundaries, increased number of grain boundaries, and deformation of particles giving them higher surface-to-volume ratio.
The exact nature and appearance of the surface layer differs between different alloys and is also a consequence of the specific processing route of the material. Sometimes the term “near-surface deformed layer” is used for the surface layer heavily deformed by thermo-mechanical shearing. Such a layer has been identified in rolled products and after grinding of wrought alloys, but its existence has been questioned for extrusions in mill finish. The common feature and the important message is: The material, up to about 1 µm below the surface, normally has different properties compared with the bulk. When it comes to adhesive bonding, the key issue is that such layers can become very prone to corrosion, where attack propagates quickly and spreads under an adhesive or coating, leading to delamination. Again, this emphasizes the need for proper pre-treatment of aluminium before adhesive bonding.

Grinding also causes deformed layers (Figure 3). Depending on the abrasive parameters and the alloy, these layers can result in radically impaired corrosion properties.

3.4 Extrusions

Generally, the profiles produced by extrusion from the 6000 series of aluminium alloys are relatively corrosion resistant, with relatively small amounts of intermetallic particles, and are therefore suitable for adhesive bonding (after pre-treatment). For high-strength alloys in the 7000 series, there is a compromise between stress corrosion resistance and the mechanical properties that are achieved through advanced heat treatment. This means that corrosion properties and suitability for adhesive bonding are more varied, and it is important to understand the properties of the specific alloy in question.
3.5 Rolled material

Rolled aluminium in the 5000 series is resistant to corrosion and suitable for adhesive bonding. The deformed surface layer is only a few tenths of a micrometer thick, but some oxide can be incorporated into the deformed layers during rolling. This layer should be removed to obtain the bulk properties of the aluminium.

The sheet metal material can be bought on a roll – untreated as well as with various pre-treatments. The purpose of pre-treatment is to give the sheet metal surface the properties the customer requires: weldability (limited oxidation growth), bondability, corrosion resistance, etc. The processing times in a rolling mill are limited, which is why complete removal of the deformed layers can be difficult to achieve. Often the rolled metal is, or becomes, coated with a lubricant that a subsequent adhesive system has to be compatible with (or the surface needs to be cleaned). It can be challenging to assure the quality of the adhesive bonding process after the sheet metal has been stored, cut, shaped, handled and joined.

Alternatively, the formed sheet metal parts can be pre-treated individually just before assembly and joining.

3.6 Castings

In comparison to extruded and rolled aluminium, the surfaces of castings are more difficult to pre-treat in a way that makes them suitable for adhesive bonding. Pre-treatment becomes more extensive and involves more process steps that must be adapted to the specific material/product. One reason is the size of intermetallic particles (usually AlFeSi). Depending on the chemical composition of the alloy and heat treatment, such particles can grow up to 100 – 200 µm in size, which is much larger than normal pre-treatment processes can cope with in an efficient way. Quick cooling of the castings suppresses the growth, and certain alloying elements, such as titanium, sodium and strontium, are used in order to modify grain and particle structure.

Castings may have traces of release agents on the surface, such as graphite powder, oxides and silicon, which can affect etching, anodizing and durability of the adhesive joint. The release agent that is used must be matched with the washing/degreasing agent in the etching process. Porosity in the cast material can make it more difficult to carry out a robust pre-treatment.
4. Requirements for adhesive bonding

Adhesion forces refer to the attraction forces occurring in the interface between two surfaces in contact with each other. The attraction force between an adhesive’s molecules and the surface to be bonded is effective over a maximum distance of 0.5 nm (1 nm = one millionth of a millimeter) for chemical adhesion to occur. To achieve this proximity, the adhesive has to wet the surface.

The term surface tension is used for liquids and gases while the same thing for solid materials is referred to as *surface energy*; the units used are the same.
4.1 Adhesion, wetting and flow properties

For spontaneous wetting to occur, the surface tension of the adhesive has to be lower than the surface energy of the material to be bonded, and the adhesive must have low viscosity (Figure 4b). If the surface tension relation is reversed, the adhesive will strive to shrink to a droplet (Figure 4a). Wetting is based on the fact that everything strives for the lowest energy level.

Generally, metals have substantially higher surface energy than the surface tension of adhesives. As a result, the surface tension does not cause any problems when bonding metals. When bonding plastics, you need to be aware that many plastics have very low surface energy (e.g. PP, PE, PVF and PTFE). These plastics can only be adhesively bonded after a surface conversion that increases the surface energy.

In practice, it is the surface energy at the moment of adhesive application that is important for wetting. Manufacturing methods, possible surface treatment, handling and storage, all influence the chemical and structural properties of the surface. It is important to remember that a single layer of contaminating molecules may change the surface energy completely.

A surface that may appear smooth and even, perhaps even polished, can be very rough if examined at high magnification. To be able to penetrate into and fill out any unevenness in the surface, the adhesive must have sufficiently low viscosity. For uncured adhesives, it is usual that viscosity drops with rising temperature, and moderate heating often promotes wetting. Product examples are hot-melt adhesives and adhesive films, which are more or less solid at room temperature but which will flow when heated. Adhesive tapes are also relatively solid at room temperature (even if they are sticky). They contain high-viscosity components that flow slowly but eventually spread into cavities in the surface. The process can be accelerated by heating, but a relatively long time is still needed for adhesive tapes to obtain full strength.
4. Requirements for adhesive bonding

It is important that enough time is allowed for wetting before the adhesive sets or curing is initiated. Control of time and temperature is important for a reproducible bonding process. The use of penetrating primers can also be helpful. Saturating the surface with a penetrating primer before the adhesive is applied can also be helpful to overcome problems with time-consuming and incomplete wetting. The primer thus contributes to the higher strength and better durability of the adhesive joint. This is particularly important when bonding metals that are going to be used in corrosive environments. Poorly filled surface roughness allows space for water to penetrate, which can result in corrosion.

4.2 Cleanliness

In order for the adhesive and material surfaces to really connect with each other, the surfaces must be clean, i.e. free from grease, oil, dirt, salts and other contamination.

Some adhesives tolerate poor cleanliness. For instance, in car body applications, one-component, hot-curing adhesives that are adapted to the types of grease that exist on the sheet metal are used. Acrylic adhesives are also known to be tolerant of contaminants, as the adhesive itself acts as a solvent since it contains low-viscosity monomers.

4.3 Wet adhesion

There must be a binding mechanism or chemical interaction between the surface and the adhesive in order for adhesion to occur. However, not every form of binding is stable enough to resist the impact of another medium, such as water. As the adhesive becomes wet at the interface, the adhesion forces are reduced. If the adhesion forces are weak, the water can take over the binding sites if it proves to be a more advantageous energy state, which can result in complete loss of adhesion. The reaction can be reversible and strength may be regained if the joint dries out.

A wet gap normally has long drying time. Reduced wet adhesion can open the way for corrosion and rapid breakdown of the adhesive joint (Figure 5).

The chemistry of the adhesive is often the major factor when it comes to the quality of wet adhesion.

The composition of the adhesive also affects how fast and how much water the adhesive can absorb, which can then affect the interface between the adhesive and the material. An intact-unloaded adhesive joint can take years to saturate even in a 100% humid environment, but if there are micro-cracks, blistering and defects in the adhesive joint, it is possible for the water to quickly enter the interface. In addition, if the adhesive is exposed to a continuous load, the water’s rate of diffusion in the adhesive can increase substantially. This can occur when, for example, different materials are joined together and due to temperature changes in a humid environment.

For aluminium it is also important that the oxide is stable. It does not help if the adhesive attaches to the oxide but the oxide itself dissolves.
4. Requirements for adhesive bonding

4.4 Pre-treatment

Pre-treatment can have several purposes:

- To remove contaminants and loose oxides from the surface
- To create a strong oxide that offers good wetting and adhesion properties for adhesives and coatings
- To give the surface better durability in a corrosive environment e.g. remove deformed surface layers
- To give the surface an attractive appearance
- To create a rough surface and larger surface area that allows mechanical bonding of adhesives
- To give the surface temporary protection before bonding
In reality, the final choice of pre-treatment often needs to be a compromise. Fulfilling all requirements in an optimal way at a reasonable cost can sometimes be impossible.

4.4.1 Mechanical pre-treatment

During mechanical treatment, such as grinding and blasting of aluminium, a new deformed surface layer will be created (See Surface layers in Chapter 3).

This is the reason why adhesive joints on ground aluminium usually have poor long-term performance in corrosive environments. Corrosion tests on blasted aluminium surfaces can give different results depending on how the test was performed. The rough surface structure and larger surface area counteract the negative influence of the “deformed surface layer.” A rough surface area can give mechanical interlocking and longer pathways for the propagation of corrosion.

It is unsuitable to grind or brush aluminium with steel tools, as the surface can become activated by the residues of steel particles that may remain on the surface. Activation of the surface can lead to corrosion depending on the environment. It is recommended that mechanical pre-treatment is complemented with a chemical pre-treatment if the adhesively bonded product is likely to be exposed to a corrosive environment.

4.4.2 Chemical pre-treatment

There are many types of pre-treatment, and each involves several steps. For most metals, the first cleaning step for pre-treatments is usually an alkaline degreasing by dipping or spraying (about 50 – 60°C). This treatment removes organic materials such as oil and grease, salts and loose dirt from the metal.

The next step aims to remove the surface layer. Chemical etching can be carried out with both acids and alkalis (usually sodium hydroxide). See Figure 6. The dissolution rate of various alloying elements varies, depending on which etching solution is used.

After etching, various elements will be enriched on the surface.

In the following steps, desmutting is performed to remove intermetallic particles and enrichments of elements such as silicon, magnesium and copper and other residues from the etching process. Different concentrations and mixtures of acids are used to achieve the desired results. As an example, nitric acid has a stronger oxidizing action than sulphuric acid, which also results in the removal of particles containing copper. A common treatment has been etching in chromic acid. There are restrictions on the use of hexavalent chromium due to health and environmental concerns.

Figure 6: Scanning electron microscope (SEM) picture of aluminium surface after etching.

a) Surface that has been alkaline-etched.  b) Surface that has been acid-etched.
Anodizing is the best pre-treatment if long-term durability of the adhesive joint is required. Here, aluminium profiles are treated in the vertical anodizing line at Hydro’s manufacturing plant in Vetlanda, Sweden.
The layer of aluminium oxide and aluminium hydroxide formed after etching passivates the aluminium, but is not stable enough to resist corrosive environments.

The subsequent surface treatment steps aim to stabilize and improve the properties of the oxide. This is called a surface conversion layer or conversion layer. After this treatment, the oxide should be stable and provide good adhesion for adhesives.

Immersion in water at around 95 – 100°C for about 10 minutes after etching (Boehmitization) gives improved corrosion resistance at the interface between the adhesive/aluminium. The oxide layer grows and becomes thicker as well as becoming more stable. Although this method appears to be simple, water quality is important for the end result and the challenges of maintaining such quality in industrial production should not be underestimated.

Conversion treatments based on titanium/zirconium chemistry have become common in the vehicle industry. These thin coatings are almost always coated in an electro-dip painting process that effectively protects the oxide from exposure to a corrosive environment.

Conversion treatment with hexavalent chromium gives excellent corrosion resistance and is well documented. It is usually called yellow chromating. Following EU directives, hexavalent chromium was phased out from the vehicle industry (lightweight vehicles < 3,500 kg) in 2007 and from the electronics industry in 2006.

Conversion treatments based on hexavalent chromium are still used and are the preferred treatment for high-strength alloys in aerospace applications. This industry is exempt from regulations on the presence of hexavalent chromium in its products, but the pressure to phase out these products is increasing. There are also more environmentally friendly chromium conversion treatments that are based on trivalent chromium.

There is an intense search for conversion treatments and inhibitor systems that can replace hexavalent chromium. These include sol-gel chemistry, self-assembled mono-layers, rare earth metals, cobalt, vanadates, permanganate and molybdenum.

### 4.4.3 Primers

The primary function of primers is to adhere to a surface in order to form a good base for adhesives. Primers can have different functionalities, e.g. etch primer, wash primer or epoxy primer. These can be more or less aggressive to the materials. Some can dissolve organic contamination, others can dissolve metal oxides and some can even dissolve metal.

Primers also have to have adequate inherent strength. Primers usually contain a low-molecular epoxy binder and corrosion inhibitors that protect the interface from degradation. This means that primers are chemically very reactive and therefore pose a health risk, which requires appropriate handling and use. The purpose of a primed surface can also be to provide short-term protection of a surface during storage and handling (e.g. an anodized surface).

### 4.4.4 Electrochemical pre-treatment, anodizing

Anodizing is the best pre-treatment if long-term durability of the adhesive joint is required.

Anodizing is an electrically driven oxidation of the metal in an acidic electrolyte carried out after etching. The electrolyte continuously partly dissolves the formed oxide. There is a controlled balance between oxide formation and oxide dissolution depending on the acid and the anodizing parameters. A thin, compact, stable and electrically isolating barrier layer is formed closest to the metal. This layer contributes to good corrosion properties, even if it is only a fraction of a micrometer thick. The main part of the oxide will be porous, with pores reaching from the barrier layer to the outer surface. The porous oxide layer (pseudoboehmite) is less resistant than the barrier layer but it contributes to corrosion resistance, partly through its thickness and partly through burying the intermetallic particles that penetrate...
4. Requirements for adhesive bonding

the barrier layer. Sometimes the pores are sealed after anodizing through cold or hot process sealing.

**Chromic acid and phosphoric acid** anodizing without sealing provides a thin, high-strength oxide layer. A primer or a low-viscosity adhesive can penetrate the pores, which results in very good adhesion when the subsequent adhesive adheres to the primer. These methods are regularly used in the aviation industry. Chromic acid anodizing has minimal impact on the fatigue properties. These methods are excellent in terms of strength. However, the surface treatment does require thorough process control and the use of hexavalent chromium is questioned for environmental reasons.

**Sulphuric acid** anodizing is the most frequent anodizing process. The oxide is hot-sealed in most cases. The oxide film's pores are too small anyway to achieve good penetration with adhesives or primers. The oxide film is made relatively thick, 20 – 25 µm, in construction applications where weather resistance is required. This oxide film is brittle and can be torn from the surface and thus reduce the strength of a structural adhesive joint. Furthermore, relatively high water content in the oxide film, which is in balance with atmospheric humidity, can have a negative impact on the adhesive bonding. Thin sulphuric acid anodized oxide films of 1 – 10 µm or really thin ones,<1 µm, can give adhesive joints that are very corrosion-resistant and strong. The oxide film's properties can be significantly affected by the anodizing parameters and there are many possible processes for sulphuric acid anodizing.

4.4.5 **High-energy pre-treatment methods**

Surface treatment methods such as flame, corona, plasma and laser provide fast and local heating and local impact on surfaces. They are often used to modify the surfaces of plastics, paints and composite materials. They can also be used to clean metal surfaces from contamination. In connection with the treatment, the oxide's composition and properties can also be affected in a way that is favorable for bonding.

These technologies are expected to grow. A major advantage is that you can limit the treatment to the surfaces that are to be adhesively bonded with these “dry” pre-treatment methods.
5. Properties of adhesive joints

Adhesive joints are popular because the additive that creates the joint is made of plastic/polymer rather than molten metal. This permits the joining of different types of materials that could not otherwise be reliably joined.

Upon loading of adhesive joints, the desire is that there is sufficient adhesion between the adhesive and the bonded materials, and that the adhesion is stronger than the adhesive itself.
5.1 Failure modes

The adhesive should not “let go” from the surface and cause an adhesive failure (AF), but the fracture should occur inside the adhesive itself in a cohesive failure (CF), as shown in Figure 8. Alternatively, the adhesively bonded material should break via delamination, substrate failure (SF). The term surface cohesive failure (SCF) is often used when a very thin layer of adhesive remains on one side. This occurs for instance when a stiff structural adhesive has been bonded on a blasted metal surface. The failure is inside the adhesive but goes from edge to edge near the metal surface due to high local stresses, as there is a big difference in E-modulus between adhesive and metal.

5.2 Mode of loading

An adhesive joint can be loaded in several different ways (Figure 9 on the next page). The different load directions in the adhesive are sometimes stated in the same way as the mode of loading in failure mechanics.

An adhesive joint often works very well if loaded in shearing or compression mode. Sometimes it is even possible that the adhesive joint is constructed in such a way that the adhesive has a locking function without being load-carrying. Even in the case of a clean and uniform tension load in Mode I, the adhesive’s load-carrying ability can be of importance. However, the load tends to be slightly offset with some type of cleavage along a zone at the edge of the adhesive joint.

This load becomes unsuitable if cracks or possible defects occur. Furthermore, if the adhesively bonded materials bend or are plastically deformed, then the exposure is very high in a line along the edge, resulting in a high risk of peeling failure.

Figure 8: Schematic overview of failure modes.
Mode of loading

Tension Mode I
In an adhesively bonded joint that is exposed to tensile or compression load, the load attacks at right angles to the adhesively bonded joint.

Compression Negative Mode I

Cleavage Mode I
During cleavage, almost the whole load is concentrated to a small area of the adhesive joint.

Peeling Mode I
During peeling, the stress is limited to a thin line at the boundary of the joint. Even less adhesive than during cleavage contributes to the joint’s strength.

Shearing Mode II
In an ideally shear-loaded joint, the load attacks in the plane of the joint. The stresses are evenly distributed across the surface.

Mode III shearing at right angle against mode II

Torsion Mode II
An adhesive joint subjected to torsion can basically be equated to a joint in shear. Mode III when combined with axial load.

Figure 9: The strength of adhesive joints depends on how they are loaded.
5.3 Mechanical performance

There are no clear definitions or classifications of the mechanical properties of adhesives.

Structural adhesive, or structural bonding, usually refers to adhesives that are stiff, resistant to high temperatures and have relatively high strength, such as epoxy adhesive. The modulus of elasticity exceeds about 1 000 MPa at room temperature and the strain at failure is usually in the range of 1 – 10%.

Elastic adhesive is a term used to describe flexible and soft adhesives where the E-modulus rarely reaches more than about 10 MPa and the strain at failure is over 100%. Examples are polyurethanes, MS polymers and silicones.

Sometimes the term semi-structural adhesive bonding is used to cover adhesives which, when it comes to stiffness, are somewhere in between. These include modified polyurethanes and acrylic adhesives.

Elastic adhesives have very good impact resistance.

5.4 Structural adhesive bonding

With structural adhesive bonding, the adhesives are relatively stiff. This means that thin metals and relatively soft materials can show significant strain at loading. The strain distribution in the material means that the lap joint strength does not increase with increasing overlap, since the adhesive in the middle of the joint only carries marginal load (Figure 10). Another effect is that the joint’s strength is relatively insensitive to variation in the thickness of the adhesive joint.

![Figure 10: Basic stress distribution over a lap joint in sheet metal bonded with structural adhesive. Low stresses in the middle of the joint. High stresses at the edges A and B. The fracture can be initiated by exceeding the maximum strength or maximum strain.](image)

Strength and strain properties for adhesives

![Figure 11: Schematic overview of strength and strain properties for the most common main groups of adhesives. Observe that the absolute shear strength is dependent on the geometry of the specimen.](image)
Usually when testing joint strength, the adhesive cracks at the end of the overlapping materials where the opposing material bends and begins to deform plastically (Figure 12). The adhesives cannot handle the large local strain and the cracks tend to grow quickly through the entire joint.

As the thickness of a metal product increases, the difference in stiffness between the product and the adhesive also increases. This puts greater demands on structural design in order for adhesive bonding to continue to be a competitive joining method. Structural adhesive bonding increasingly resembles elastic adhesive bonding as the thickness of the product increases and the operating temperature rises.

### 5.5 Elastic adhesive bonding

The strongest and stiffest structural adhesives do not necessarily result in the strongest joints, as adhesive joint strength also depends on the properties of materials and how the joint is designed.

With elastic adhesive bonding, you use the adhesive’s deformation ability to spread the load over the entire adhesive area (Figure 13). If the overlap is larger, the joint’s load-carrying ability also increases.

In general, you should never use an adhesive that is stiffer than you require.

It is difficult to compare strength results between shear strength tests with different geometric configurations, so shear strength testing is essentially a qualitative test method for comparing samples with the same configuration. An inspection of the fracture surfaces to verify that the adhesion is good tends to be the most important aspect.

As a joining method, adhesive bonding is most favorable when the materials that are to be joined together are relatively thin-walled, since the adhesive spreads the load over a large area. This is achieved without affecting and weakening the materials, as is the case in welding, and without causing high local stress concentrations, as is the case in riveting, for example.
In order for the adhesive to be loaded evenly, it is important that the joint is relatively thick and that the adhesive has a smooth and well-defined distribution over the joined area.

Elastic adhesive bonding can tolerate large deformations without breaking, energy absorption is high, and possible loading in peel is distributed over a very wide area. Elastic adhesive bonding facilitates joining together materials that have different thermal expansion coefficients and it is a suitable choice when large panels are to be bonded onto a structure.

An elastic joint will not be as stiff as a structural adhesive joint but it can achieve very good strength, impact resistance and crack resistance, which may make it more functional.

5.6 Joint design

Adhesive joint design is of great importance. The cylindrical adhesive joint is as close to the ideal as you can get (pin in hole, tube in tube). This configuration is exposed to shearing stresses regardless of whether you apply pressure, torsion or a tensile load.

Differences in thermal expansion coefficients should be taken into consideration. The joint’s edges are always subjected to the greatest stresses.

A rule of thumb about how much an adhesive joint can be loaded is that the peel, shearing and compression ratio is approximately 1:100:1000.

When a joint’s load-carrying ability cannot be increased by increasing the overlap of the joint (Figure 14), the joint can instead be designed so that loading will be more evenly distributed over the adhesive joint (minimize edge effects).

Designing according to joints 1–4, Figure 14, makes the material more formable at the edges. Such features can often be incorporated in the design of an extrusion. The intention is that the material should deform before it transfers loads that are too high for the adhesive joint. Another option is to make the adhesive joint considerably thicker around the edges, as in joint 5. This results in an adhesive joint with a larger deformation zone. Joint modification is of the greatest use when using stiff adhesives.
5.6.1 Combined or hybrid joining

Adhesive bonding can be combined with different joining methods in what is known as hybrid joining. Depending on adhesive and choice of material, as well as joint configuration, the role of the adhesive can range from solely load-bearing, to simply sealing the joint. If correctly constructed, these joints can utilize the advantages of both joining methods.

With structural adhesives the adhesive becomes the primary load-bearing component. In the case of elastic adhesives, the spot mechanical joint tends to be stiffer than the elastic adhesive joint. If the thickness of the adhesive joint varies, it is mainly the mechanical joint that is the load carrier.
Elastic adhesive bonding needs a certain defined joint thickness to spread the load. This is difficult to achieve through instantaneous fixation with a mechanical joining method, as the adhesive is squeezed locally until the materials are in contact. One way to solve this is to create local elevated features in one of the components that allows the materials to come in contact with each other. In these local spots, mechanical joining techniques can be used for fixation or for adding strength to the joint. The load distribution can be very difficult to predict and each specific product therefore has to be analyzed based on its properties.

### 5.6.2 Innovative joints

There are many variants of innovative joining constructions where mechanical locking can be used. The materials are then mechanically fastened to each other and the adhesive’s function is to lock the materials and thereby prevent the parts from separating. The joint can thus transfer a high load, but the load on the adhesive is still low and in a favorable loading direction. Mechanical insert joints such as spring and groove joints are common examples (Figure 16). Although self-locking joints have many advantages, they can be challenging to handle in automated production.

Apart from mechanical locking, many other advantages can be achieved with a good joint design. Some examples:

- Components that are self-aligning or self-fixating
- Adhesive traps that deal with excess adhesive
- Channels for injection of adhesive
- Simplify assembly and fixation or facilitate handling
- Joints that efficiently compensate for manufacturing tolerances

Aluminium extrusions with their flexibility in design and geometry are particularly suitable for creating different types of innovative joints.
An aluminium profile bonded to formed aluminium sheet with epoxy primer coating.
5.7 Factors that have an impact on joint quality

During use, an adhesive joint is exposed to mechanical loading and the environment, which affect and degrade the properties of the joint. A joint that fulfills its function for the entire specified service life under the specified conditions is of good quality.

To achieve adhesive joints with good long-term properties, you need to have a good understanding of how different factors, partly by themselves and partly in combination, affect the quality and degradation of the joint.

The strength of an adhesive joint is affected by external factors such as water absorption, UV exposure, softening if it is heated or creep under loading.

5.7.1 Weak boundary layers

What we consider as aluminium is in fact an aluminium alloy coated with an oxide. The oxide is primarily aluminium oxide (alumina), but it can also contain oxides of other alloying elements, and the composition depends on the production process.

This surface can be covered with grease and dirt, adsorbed molecules from gases and fluids, or products from chemical reactions between the material and the surrounding environment.

If a surface is contaminated or the surface itself is weak, then it can result in a weak link in the adhesive joint, known as a ‘weak boundary layer.’

This is likely to manifest itself as a transfer from a fracture in the adhesive to a fracture between the adhesive and the material with great variation in strength between different specimens. The sensitivity to different types and amounts of contamination shows great variation between various adhesive systems.

The oxide layer can be transformed, resulting in lower strength and/or a change in volume, which can cause internal stresses in the adhesive joint.

Salts that remain on the metal surface underneath the adhesive can, if exposed to moisture, speed up corrosion in the joint.

The adhesive joint’s strength becomes dependent on the weakest link in the chain in the environment that the joint will be exposed to. This is schematically illustrated in Figure 17.
5.7.2 Mechanical loading and synergy
Adhesive joints are normally considered to be fairly insensitive to vibrations and fatigue at higher frequencies. Often the adhesive joint is used as vibration damping and crack stopper. High continuous mechanical loads can cause creep and plastic deformation in an adhesive joint. What is more common is that the interface problems are already worsened at lower loads as water can more easily penetrate the joint. The concurrent effects of temperature, environment and mechanical loading work together in synergy, which can give rise to considerably faster deterioration of strength than if the effects of these three influences were added separately.

When exposed to loads, major stress concentrations occur at the edges of the adhesive joint, where the environmental influence is also most severe. This can result in quicker degradation of the adhesive joint than would otherwise be the case. It is therefore important to construct the adhesive joint in such a way that it minimizes stress concentrations.

5.7.3 Temperature
All plastics and therefore all adhesives are visco-elastic. From a loading point of view, they are thus more affected by temperature and time than metals, for example. They become softer at high temperature and harder at low temperature. This also means that you cannot use set values for a large number of strength parameters for an adhesive, such as modulus of elasticity, yield point in tension and creep strength. These values are affected by the temperature and are also dependent on the speed of deformation.

The adhesive has to have acceptable properties in the whole temperature interval that it may be exposed to. For example, stiff and high-strength structural adhesives are often used because they have good high-temperature properties.

An adhesive’s properties are most temperature-dependent close to the polymer’s glass transition temperature, Tg. This is the temperature at which large movements can occur in the polymer chains. This means that the material softens above this temperature. How Tg relates to the operating temperature can be critical. An elastic adhesive can set at low temperatures and become more sensitive to stress concentrations and shock loading. At high temperatures, the ability to resist creep under loading reduces for adhesives. If the adhesive joints are exposed to a long-term load at high temperature the adhesive’s creep resistance must be good enough.

Adhesives that cure without heat input can rarely be used practically at temperatures exceeding 100°C. There are very few adhesives that can practically be used at temperatures above 300°C. The adhesives that are the most heat resistant tend to become very hard at low temperature. Silicone adhesives are an exception. These are soft, flexible and can be used up to about 250°C. There are thus inorganic adhesives that are able to withstand higher temperatures.
5.7.4 Environment and corrosion

Corrosion properties are controlled by the choice of alloys, the finish of the alloy, surface treatment as well as by the properties of the polymer/binding agent that adheres to aluminium.

One factor that is crucial for an adhesive joint’s function is that it adheres well to the substrates and that this adhesion persists during the loading the joint is exposed to. There are extensive test results and knowledge of different adhesives’ durability in different environments.

When bonding aluminium, inadequate strength of the adhesive joint is often a boundary layer problem, i.e. an unwanted effect at the boundary layer between the adhesive and the aluminium oxide. This is described in “Surface layers” in Chapter 3.

Water, whether it is in liquid or vapor phase, is one of the most common and most severe environmental impacts that an adhesive joint between metals can be exposed to. In addition, if the water is saline, then the boundary layer is even more negatively affected as the presence of an electrolyte allows corrosion. A surface conversion has to be carried out before adhesive bonding to increase the adhesive joint’s durability, primarily to prevent initiation of corrosion.

For some adhesive systems, it may be heat and high humidity, possibly together with mechanical load, that limit the service life of the joint. However, it is more common that it is exposure to a corrosive environment that sets the limits.
The environments that are most corrosion-active are found along coastlines, on roads that have been treated with road salt, and in heavy industrial environments in temperate climates.

Wet time, i.e. the time an electrolyte is present, can be of importance. In warmer climates, corrosion occurs more quickly, but the corrosion stops when the electrolyte has dried up. The composition of salts and possible dirt deposits on the surface is also of importance. Magnesium chloride and calcium chloride bind more moisture than sodium chloride and are also acidifying. This makes the electrolyte more aggressive as well as making it active for a longer period of time.

Moisture reaches the boundary layer between the adhesive/aluminium by penetrating irregularities on the aluminium surface that have not been filled properly. Moisture can also diffuse through the adhesive. For a good adhesive, it can take years to saturate a thin adhesive joint with about a 12 mm overlap with moisture, while the overlap's edges are exposed almost instantly. The long-term strength of adhesive joints that are exposed to moisture is therefore very dependent on how well the adhesive fills the surface roughness and on the strength and durability of the aluminium oxides that the adhesive bonds to.

There are several forms of corrosion with different mechanisms. The most relevant for adhesive bonding of aluminium are: galvanic corrosion, general corrosion, crevice corrosion and filiform corrosion. The latter is illustrated in Figure 20.

Galvanic corrosion occurs when two materials with different corrosion potentials are in electrical contact with each other and at the same time exposed to an electrolyte. The rate of corrosion is proportional to the galvanic current between the materials. The less noble metal will dissolve (anode). At the nobler metal (the cathode), the oxygen is reduced to hydroxide ions. An adhesive can isolate the materials from each other and therefore prevent galvanic corrosion.

General corrosion is usually a slow process on aluminium but the rate is increased by high temperature, low pH value, the presence of chloride ions and the presence of an oxidizing agent.

Crevice corrosion can occur in direct connection to the adhesive in an incompletely filled adhesive joint.

Once a small crevice has formed underneath the adhesive and in the presence of saline water, the propagation can proceed very quickly as the process catalyses itself. The corrosion front has a very low pH (close to 1), which dissolves the aluminium oxide, while the moisture can reduce adhesion. The pressure exerted by voluminous corrosion products also loads the crack tip mechanically. If this corrosion process takes place underneath a coating, it is called filiform corrosion, as the coating deforms and the corrosion continues in the shape of threads (filaments). Underneath an adhesive, the corrosion products expand the joint in all directions. Often this becomes a semi-circular delamination front. The circle's radius is a function of the joint's stiffness.

Apart from the surrounding environment, the composition and form of aluminium (extrusion, rolled metal, temper, etc.) have significant influences on how quickly the initiation phase and propagation phase proceed.

If there are remaining surface layers, the autocatalyzed corrosion process can propagate very quickly in the surface layers underneath the adhesive. The consequence is that the system's life largely becomes dependent on the time until initiation.
The time for initiation can effectively be prolonged if the joint is painted, which prevents salt from reaching the surface of the aluminium. Electro-dip paint is particularly good for protection, as the electric field builds the paint layers to full thickness all the way to the adhesive.

### 5.7.5 The impact of pre-treatment

Adhesive bonding of aluminium in an “as received” condition is relatively bad from a corrosion point of view. Epoxy adhesive joints on untreated extrusions in alloy 6060 that are exposed under a truck that drives on roads treated with road salt, do not have much more than one year’s service life. At the same time, adhesive joints on etched aluminium are very good and adhesive joints on anodized aluminium are basically intact. This shows how important it is to remove the surface layer if the bonded profile will be exposed to salt and moisture. Paint or coatings keep the salt away and thus delay the initiation of corrosion.

Corrosion inhibitors in primers and relaxing elastic adhesives can be practical options if the environmental influence is moderate and not too humid.

Coated extrusions or pre-coated sheet metal may be joined satisfactorily with elastic adhesive bonding. High-strength adhesive bonding of painted surfaces will be limited by the strength of the paint system. The adhesive should be considerably more elastic than the paint to obtain an advantageous load distribution.

It is slightly contradictory that a permanent adhesive tape can work well on aluminium in as-received condition as long as the surface is relatively clean, e.g. after wiping with isopropanol. Adhesive tape and elastic adhesive systems have the advantage of relaxing, and as a result, the mechanical load does not concentrate at the crack tip as corrosion products swell (Figure 20). Many adhesive tape products are diffusion-resistant to moisture. Furthermore, materials such as adhesive tape can also have some self-healing properties after drying and temperature changes. These flexible systems, combined with a basic surface treatment on aluminium, can therefore be useful and cost-effective solutions where structural adhesives demand much more advanced surface treatments.

![Figure 20: Schematic overview of filiform corrosion.](image-url)
6. Groups of adhesives

Adhesives can be divided into groups based on the way they set and on strength. These groups are in turn divided into adhesive types, based on chemical structure. The naming of these is not consistent, nor logical. Their names can be taken either from the binders or the reactive groups in the adhesive. Adhesives are normally a mixture of several chemicals, which often makes the naming of the adhesive type only part of the truth.

Curing adhesives represent the main group and include many types of high-performance adhesives. This group also includes the most suitable structural adhesives for aluminium.

In this chapter, we will provide you with a general description of the adhesive groups, and the key properties of the most relevant curing adhesive types for aluminium.
6.1 Curing adhesives

Curing adhesives set through cross-linking of chemical reactive groups between the multi-functional polymers, as these polymerize into a three-dimensional structure. The curing reaction is not reversible.

An adhesive is based on a mixture of different base polymers, possibly also monomers, reactive groups, fillers and additives. The additives can be, for example, various modifiers, accelerators, inhibitors, pigments and adhesion improvers. This gives nearly endless permutations for producing adhesives with tailored, advanced and specific properties.

6.2 Epoxy adhesives

Epoxy adhesives are the most common type of structural adhesive. They have very good adhesion to most materials: metals, plastics, composites and ceramics. Epoxy resins are relatively stiff, strong and brittle, but with a modified chemical base, the impact resistance can be excellent. Epoxy resins can also occur as an adhesion provider in many other adhesives.

---

**The curing can be initiated by:**

- **Mixing**: Two or more components are mixed with each other
- **Heating**: Curing is initiated by heating the adhesive
- **Moisture**: The adhesive absorbs and reacts with humidity
- **Ultraviolet light**: UV light activates the setting agent in the adhesive
- **Anaerobic environment**: Anaerobic adhesives cure in contact with metal ions and in the absence of oxygen
- **Combination**: There are adhesives that combine several ways of curing or reactive groups, e.g. moisture curing hot-melts

**Epoxy adhesives, summary:**

- Curing at room temperature (2-component) or at elevated temperature (1-component)
- The curing time can vary from a few minutes up to 24 hours
- Very high strength and relatively low fracture strain
- Very little shrinkage during curing, about 2%
- Good heat resistance
- Very good chemical resistance
- Excellent adhesive for metals and also suitable for most other materials
6.2.1 Polyurethane adhesives, PUR

Polyurethane polymers are characterized by being flexible, tough and by having high strength. Since the degree of cross-linking can be varied, polyurethane adhesives can be designed to fill various needs, from very flexible sealants to high-strength structural adhesives. The main niche for polyurethane adhesives is elastic adhesive bonding. Polyurethane adhesives have very good adhesion to most non-metallic materials. Their adhesion to metals can be relatively weak, but there are many modified polyurethane adhesives where this adhesion is excellent.

Using a primer can also be a good solution. Polyurethane adhesives can stiffen substantially at very low temperatures as their area of use usually exceeds the glass transition temperature (Tg).

Figure 21: Strength of some of the different groups of epoxy adhesives at different temperatures. The blue curves show the same adhesive cured at RT (room temperature) and at elevated temperature.

**Polyurethane adhesives, summary:**

- Curing at room temperature
- 1-component, elastic, cures with moisture, about 3 – 5 mm in 24 hours
- 2-component, elastic and high strength, cures by adding moisture or alcohol or a mixture of setting agent and base. The curing time can vary from a few minutes to days
- Very good impact resistance
- Works well for plastics and different combinations where plastics are included
- Can contain free isocyanates which can evaporate at increased temperature
6.2.2 Acrylic adhesives

Acrylic chemistry is more versatile with more formulation variables than polyurethane and epoxy chemistries. The main group that is the most relevant for the structural adhesive bonding of aluminium is MMA adhesives (elastomer-modified Methyl Meta-Acrylic-based adhesives).

MMA adhesives give off considerably less of an odor than meta-acrylic adhesives, but the odor is nevertheless offensive. If the methyl group is exchanged for heavier molecules, the odor can be decreased further, but that entails a strong and often negative impact on other properties, as well as the price. There are examples of such adhesives for special applications.

In terms of strength and strain, MMA adhesives are placed between epoxy and polyurethane. They are known for having very good adhesion to many different surfaces and surfaces that are not entirely clean. They contain a large share of low-molecular polymers and monomers that can partly act as a cleaning solvent prior to curing and partly wet the surface.

Another great advantage of MMA adhesives is that the curing mechanism (free radical polymerization) offers possibilities to provide the adhesives with better-adapted curing properties. The open assembly time is the time during which the adhesively coated surfaces have to be put together to ensure enough adhesion. MMA adhesives have a relatively long open assembly time in relation to the curing time that is required for the joint to achieve enough strength so the product can be handled (Figure 22). The acrylic adhesives can, to a very large extent, be formulated to achieve the desired curing properties.

Figure 22: Basic difference in curing speed between room temperature-curing acrylic adhesives and epoxy adhesives. One advantage of acrylic adhesives is that they can cure faster and still have enough open assembly time.

MMA adhesives, summary:

- Curing at room temperature
- 2-component, cures by mixing, but there are special types where base and setting agents are applied separately and react quickly when put together
- Very fast curing can be achieved within a few minutes up to hours
- Tolerate somewhat unclean (oily) surfaces
- Medium strength and medium strain at failure make these adhesives very suitable for joining different materials
- Many commercial varieties with somewhat different properties
- Strong odor
Other adhesive types based on acrylic chemistry are cyanoacrylate adhesives and anaerobic adhesives.

Cyanoacrylates are sometimes called “super glues.” Cyanoacrylate adhesives have good adhesion to most materials: metals, plastics, composites and ceramics. They are relatively stiff and brittle. The adhesive joints are very thin as the adhesives do not fill gaps. They are often used during assembly work and when adhesively bonding small surfaces. They cure very fast when in contact with humidity in the air, from 10 seconds to a few minutes. They have relatively low strength, medium heat resistance and resistance to chemicals.

Anaerobic adhesives are often called “locking adhesives.” Their areas of use include screw locking and cylinder joining for metallic surfaces. They are 1-component adhesives that cure when in contact with metal ions and in the absence of oxygen, with curing time from 10 minutes to about an hour. They have good heat resistance. Curing may not occur if there is oxygen present or the percentage of metal ions is too low. Aluminium with a very low copper content, and anodized aluminium, are examples where a surface activator or heat may be required to cure the adhesive.

6.2.3 MS polymer adhesives
MS polymer adhesives are based on a curing chemistry that does not contain any isocyanates but consists of “modified silane,” hence the name MS polymer.

MS polymer adhesives were developed as an alternative to elastic silicone and polyurethane adhesives/sealing compounds. This is due to the limited paintability of silicone adhesives, while polyurethane adhesives contain isocyanates and can be sensitive to UV light.

6.2.4 Silicone adhesives
Silicone adhesives are elastic and have low strength. Their unique advantage is their high heat resistance, 250 – 300°C. Silicones retain their elasticity even at low temperature.

MS polymer adhesives, summary:
- Curing at room temperature
- High strain at fracture and low fracture loads
- 1-component, moisture-curing, curing time up to several days
- 2-components, high mixture ratio 1:100, curing time in hours
- Peel resistance and cold resistance
- UV light resistance
- Paintable
- Isocyanate-free and silicone-free

Silicone adhesives, summary:
- Curing at room temperature
- 1-component, cures with moisture, and 2-component, cures by mixing
- Curing time is relatively slow, from a couple of hours up to days
- Small shrinkage during curing
- Medium strength
- Good adhesion to most materials
- Very good heat resistance
- Good resistance to chemicals and environmental impact
- Usually not paintable
6.3 Drying adhesives

Drying adhesives set by evaporation of an organic solvent or water. Usually 20 – 25% of the adhesive remains after drying. At least one of the materials has to be permeable to the drying component and they have limited usage for metals. Water-based systems are preferred from an occupational health point of view.

**Drying adhesives, summary:**
- Liquid form, 1-component
- Stiffens at room temperature
- Relatively long fixation time during solidification (drying)
- Low strength but often quite tough
- Very large shrinkage
- Limited use on metals
- Can be dissolved by the original solvent

6.4 Hot-melt adhesives

Hot-melt adhesives consist of thermoplastics that are applied when heated and which then stiffen and become firm at room temperature. These adhesives have low viscosity at the application temperature, 100 – 250°C. They do not react with the material, so adhesion relies on relatively weak cohesive forces.

Hot-melt adhesives are advantageous from an occupational health perspective, as they do not contain solvents and are not chemically reactive.

Hot-melts can be suitable for aluminium and for sealing applications. The adhesive can be applied in solid form such as a foil or film on the metal that is heated to form a joint. Preheating of the aluminium can also be a way of increasing the open assembly time of the adhesive.

**Hot-melt adhesives, summary:**
- Short fixation time during cooling/solidification
- Solidify at room temperature
- Low strength and poor heat resistance
- Heating leads to remelting
- Limited use on metals
6. Groups of adhesives

6.5 Adhesive tape

There are many different adhesive tapes on the market. These products can vary in type of adhesive, thickness, carriers, color and cell structure. One characteristic of an adhesive tape is that it neither stiffens nor cures. Adhesive tapes are a high-viscosity permanent plastic liquid. They require contact pressure, time and a certain temperature to get close to the surface, flow out, wet and adhere to the materials. Adhesive tapes do not work as well at high static load and increased temperature, but if these conditions are avoided, adhesive tapes are useful when joining aluminium or when joining aluminium to other materials. Figure 23 shows how the usage of primer during adhesive tape bonding can increase the likelihood of a good bond.

Adhesive tape, summary:
- Applied in solid form
- Need clean surfaces
- Can provide immediate adhesion and handling
- Does not require fixture time
- It takes one to a few days to develop full strength, adheres faster at increased temperature
- Flows at high static load
- Tough and strong under dynamic load
- Sound-absorbing
- Good corrosion properties
- Deformation-resistant, elastic and to a certain degree “self-healing”
- Poor heat resistance
- Easy to place the correct amount of tape at the right place
- Excellent adhesive for metals and also suitable for several other types of materials
6.6 Designed and modified adhesives

There are adhesives that can be difficult to categorize into any of the usual adhesive groups, as they are mixtures of different polymers and curing systems. They have been developed to obtain specific properties that exploit the advantages of each material and minimize their drawbacks. Often, the aim is to achieve unique process properties.

**Designed and modified adhesives, examples:**

- Hot-melts that cure with the help of moisture to achieve high strength
- Tape/adhesive in film form that is applied like a normal tape but has a built-in curing system that after heating results in a strength on par with a structural adhesive
- Adhesives that solidify to a firm gel during preheating, which then cures completely at a higher temperature
- Adhesives that are designed with mixed phases where one phase is cross-linked and gives strength while the other phase provides plasticity and impact resistance
Choosing an adhesive can be a time-consuming and demanding process. It is important to find out what conditions will apply, what function the adhesive should fill, and which properties are needed. Testing of different adhesive systems is usually necessary. The performance of the adhesive system under the conditions relevant to the specific product is an obvious focus for testing. However, various tests can also be part of the quality assurance routine for a manufacturing process.

One usually chooses an adhesive system for which there is previously good experience, as it can take a long time and be difficult and costly to verify all aspects of an adhesive system, especially the long-term properties. Taking advantage of the experience of different adhesive suppliers can be helpful. Data from earlier tests may be available, and if test conditions were not optimal for the new project, the data may serve as guidance for further investigations.
7.1 Technical specification and requirements

It is a good investment to create a detailed technical specification as early as possible in the process of choosing an adhesive, and then continuously update the specification.

In some projects, certain requirements that influence the rest of the development process can be set at an early stage. For example, if it has already been decided that the product will be anodized with sulphuric acid, then efforts should focus on finding adhesives that show good performance on such a surface. If the product will be painted, it is relevant to start thinking about whether painting will be performed before or after adhesive bonding. Based on the requirements, the ability of different adhesive systems to satisfy all the necessary functions, directives and regulations are evaluated. The technical specification defines the conditions and the tests that are needed.

It is also important that you use relevant test methods. This applies especially to verification of long-term properties for which complex interaction between various degradation mechanisms can exist. It requires understanding and skill to select appropriate test methods and to correctly interpret the results.

7.2 Product properties

7.2.1 Stiffness

Stiffness is a primary product property that often dictates the design. Stiffness is usually created by using beams with thin walls and large cross-sections. Even if the adhesive is considerably weaker and more elastic than the materials that are joined, an adhesive joint is normally stiffer than spot joints. Adhesives bind large areas, and as a result, the adhesive contributes to the stiffness of the product, especially when the material has thin walls. The loads are distributed over a large joint area, which reduces the local stresses.

7.2.2 Fatigue

Generally, adhesive joints have high fatigue strength. When fatigue tests of adhesive joints are compared to other joining methods, the adhesive joints generally show very good results. In practice, the fatigue strength is rarely constraining for adhesive joints.

When we compare a lap joint that is underfilled with one that has excess adhesive outside the joint, or where the thickness of the adhesive increases towards the lap-joint edge, we find that the load required to initiate a crack can be a magnitude lower for the underfilled joint, due to the high stress concentration. Even so, the fatigue strength is rarely a problem for adhesive joints.

7.2.3 Impact resistance

Impact-resistant adhesives are often characterized by high elongation at break. No matter how good the impact properties of an adhesive are, the energy absorption in the adhesive joint is only a fraction of what usually can be absorbed in the base materials. At impact, it is typically the occurrence of peel and cleavage forces that initiate the fracture. The design is therefore very important. The adhesive’s function is to create a joint with sufficient impact resistance to prevent buckling of material sections. Since the integrity of the joint is maintained, deformation will be limited to the area of the product chosen during the design process.
7.2.4 Recycling
Adhesive joints are often difficult to disassemble and are therefore not the best choice when recycling is a requirement. However, heating above the adhesive’s glass transition temperature (Tg) can facilitate dismantling, though you should take care with polyurethanes as isocyanates can be formed during heating. The simplest way of dismantling a product with an adhesive joint is to cut around the joint and remove it. Elastic adhesives can be cut off with a knife or thread.

From an environmental point of view, it is desirable to recycle aluminium. Small residues of adhesive on the aluminium surface will not pose a problem during remelting.

Adhesive bonding can be an appropriate method for repairs.

7.2.5 Other product properties
There are several other product properties that can be important for the choice of joining methods. For adhesive bonding, additional functionalities may be required to fulfill these needs. Many product properties relate to the environment where the product will be used. What are typical and extreme values of temperature and humidity? Is the environment corrosive or not? Can the joint serve as a seal against liquids and dust? How can joining be made a part of the acoustic design of the product?

7.3 Process properties
It is important to choose an adhesive system that allows a rational manufacturing process. The number and complexity of processing steps normally drive the cost, even if adhesives can be quite expensive. Different adhesives have different requirements at each stage of the process, affecting which steps are necessary and how quality assurance is carried out at each step.

7.3.1 Pre-treatment in production
The adhesive system’s need for surface treatment to achieve the required life in the specific environment is one of the largest costs. The investment that the installation of a surface treatment plant entails, particularly for wet chemical processes, is one of the greatest barriers to introducing adhesive bonding processes. Another factor to consider is the health issues that arise with production.
7.3.2 Application
The application of adhesives should be automated to get the correct amount of adhesive in the correct place. There are many qualified systems available. During joining, it is important that the components are brought into close contact. The adhesive should be squeezed into position and not sheared. Shearing leads to poorly filled joints. Adhesive tape and the injection of adhesives are techniques that can rationalize production and for instance improve the working environment by reducing health risks. For manual application, it is important to consider how application should be carried out (see below).

A few simple things to consider:

- How is the part maneuvered into the best position?
- How and where should you stand to move easily and freely?
- Can you attach a guide pin to the application nozzle?
- How do you deal with adhesive smudging?
- How are the parts brought together?

7.3.3 Fixturing
Some adhesives can be cured quickly using a variety of local heating techniques, i.e. hot air, induction or IR, but often the component is fixed by combining the adhesive joint with another joining method to form a hybrid joint. This gives the joint instantaneous fixation and strength. A fast-curing adhesive or an adhesive tape can be used for fixturing as well. More or less sophisticated temporary fixtures may also be necessary. If components need to be fixtured for long curing times, the investment and maintenance cost of fixtures can be significant. On the other hand, fixtures may offer an opportunity to balance and even out deviations and variations in the geometry of the components.

7.3.4 Curing
Room temperature-curing systems can be accelerated with a moderate increase in temperature. In this case, the “Arrhenius’ rule of thumb” is useful. For every 10°C increase in temperature, the chemical reaction rate is basically doubled, i.e. the curing time is cut in half. For heat-curing adhesives, the cure temperature is normally considerably higher than the maximum operating temperature. Differences in thermal expansion between materials can cause temporary deformations in the components of the product. If these deformations exist when the adhesive cross-links and the curing locks the geometry, the product is prevented from returning to its original form during cooling. This results in residual stresses in the adhesive joint or a product with geometrical deviations. The extent depends on the specific adhesive’s creep or relaxation properties. Note that variations in the rate of heating or cooling of different parts of the product can also cause these effects.

During curing, the adhesive’s volume is somewhat reduced as the cross-linking reactions result in “chemical shrinkage.” Resins normally have chemical shrinkage in the order of 1 – 5%. As adhesives are polymers, the shrinkage during cooling is larger than it is for metals and most composite materials. If the adhesive joint is prevented from contracting in the joint’s thickness direction during curing, the quality of the adhesive joint can be affected negatively, leading to cracks, air bubbles, loss of adhesion, or so-called “kissing bonds” (surfaces that are in contact but without adhesion). Spacers or shims that are used to maintain the controlled thickness of the joint must therefore not be too stiff or rigid if the product itself is stiff, as this can prevent the joint from contracting. When it comes to film adhesives, a nylon net is often used as spacer.

Two-component adhesives that first cure at room temperature may require post-curing at a higher temperature in order for the adhesive to cure fully and achieve its maximum strength. In the same way as for heat-curing adhesives, joints of this type can be exposed to loads, deformations and possible initiation of defects when passing through the oven.
8. Testing and verification

All testing, simulation, and calculation activities are performed to ensure that the joining process and the product fulfill the requirements.

The aim of adhesive testing is to understand the properties of the system so that the person who sets the requirements can feel confident that the adhesive bonding process works as intended and delivers the required product and production properties.

Tests can be performed to understand how the system works, to verify that the requirements are met, and to produce material data for calculations and for quality assurance in manufacturing. The scope and focus of testing will therefore depend on what data is already available and how demanding the specific product application is.
8.1 Qualification

The purpose of qualification testing of the complete adhesive system is to verify that all properties meet the requirements. The list of requirements and conditions can be long, which means that testing will be extensive and time-consuming. At the end, only a limited number of adhesive systems will pass the necessary steps in qualification testing. This means qualification testing of the adhesive system should be completed before the product development process begins to ensure that the product is designed to meet the relevant conditions and properties for the approved adhesive systems.

The properties of an adhesive are always a compromise and it is difficult to change a particular property without changing others as well. This means that modification of an adhesive initiates a completely new qualification cycle, the extent of which is determined by the person who makes the requirements.

**Aims of testing:**
- How the system works
- Requirements are met
- Material data for calculations
- Quality assessment

8.2 Quality assurance

Quality assurance should ensure that the adhesive system and the product work as intended. Generally speaking, all functions such as adhesion, adhesive defects, degree of curing, expected service life in different environments, etc., are difficult to verify without destroying the adhesive joint and the product.

The main focus is therefore on controlling all the steps in the manufacturing process. How this is implemented in practice can vary greatly between different products and applications.

A suitable method for quality assurance in the manufacturing process is to draw up a quality assurance plan based on the technical specification, completed testing and Failure Mode Effect Analysis (FMEA) of the manufacturing process. The plan contains clear work instructions, activities in production that facilitate work, prevent the possibility of making mistakes, and minimize the need for inspection and testing.

The purpose is to create a robust process with a known process window. Initially, testing and inspection can be more extensive in order to verify the process windows. The aim is to check what is important. At the same time, it is an advantage if the selected parameters are easy to control, or can be controlled automatically. A simple test verifying that everything works can create confidence, but it is important to ensure that what is being tested is relevant.

Often methods of non-destructive testing (NDT) are mentioned. Generally, the adhesive joints are difficult to access, and information about the adhesive joint’s quality is therefore limited. Inspection methods such as ultrasound and x-ray can verify the presence of a pore-free adhesive, but not the degree of adhesion.

8.3 Modeling of adhesive joints

To meet the demands for shorter development times, verification of the product and the production process is a necessity. Isotropic materials such as metals and plastics are relatively easy to model. Anisotropic composite materials are more difficult, but they can be modeled with accuracy today.

For welding and mechanical joining, the modeling method is well developed. For adhesive bonding and modeling of failure behavior, there is a general shortage of reliable and verified simulation methods and relevant material data. Adhesive fractures are difficult to model, especially in cases with different temperatures and where materials with different thermal expansion are joined together. It also means that the components’ geometry is of great significance for the load.
on the joint. In addition, the forming methods are of significance, as residual stresses affect the load on the joint at different temperatures. If information about materials and verified methods is missing, this results in uncertainty, which means that higher safety factors than necessary must be chosen.

8.3.1 FE modeling
Modeling of an adhesive joint can be done both with analytical models and by using finite element (FE) software. This section focuses on FE modeling. One of the advantages of using FE modeling is that it permits analysis of geometrically complicated joints loaded in many different ways, while the analytical models are often limited to very simplistic geometries and loads.

There are a number of material models to choose from for FE modeling. The choice depends partly on the purpose of the modeling, and partly on the type of problem. Figure 25 (on the following page) shows an outline of different material models and what they can be used for.

When it comes to modeling of stiffness, a group of material models can be used that are based on considering the adhesive as a continuum. This group includes linear-elastic, hyper-elastic and elastic-plastic material models, where the latter two exhibit non-linear stress-strain behavior. If properties such as creep in the material are also of interest, visco-elastic material models can be added. The disadvantage of using continuum-based material models is that the stress and strain measurements often become singular where fracture tends to occur, such as at sharp corners. This makes it difficult to define a failure criterion that works.

A cohesive material model should therefore be used to analyze the fracture behavior of adhesive joints. If the cohesive law is available, it can also be used for modeling of stiffness. The cohesive material model is based on a stress-strain relationship where a defect is initiated at a certain stress level. The extent of the defect increases in accordance with a cohesive law that is based on the amount of energy the adhesive can absorb before it breaks completely. Stress concentrations are avoided by having a zone with damaged material with degraded mechanical properties preceding the crack tip.

In a global model, only cohesive elements should be used to calculate the adhesive joint’s stiffness and strength, as illustrated for the car in Figure 25. In a local model of a test specimen, for instance, continuum-based elements with elastic or elastic-plastic material models can also be used on both sides of the cohesive elements. In the general case, energy can be released in the adhesive joint via both crack growth and through plastic strains. In this case, the cohesive elements therefore provide failure properties, while the continuum elements can supply plasticity (something which is not included in the cohesive laws). Note that cohesive material models do not work as well for elastic and soft adhesives.
Modeling of adhesive joints is a complicated subject. The shortage of relevant materials data is sometimes the biggest obstacle to carrying out a successful simulation. This shortage is mainly caused by the fact that adhesives’ properties depend on many external circumstances. An adhesive is a polymer and therefore visco-elastic. For an adhesive that is far below its glass transition temperature (Tg), the visco-elastic effect is small. However, when you get closer to Tg, the visco-elasticity increases. Apart from time and temperature, the adhesive’s properties are also dependent on strain rate, humidity and thickness of the joint, for example. Suppliers of adhesives are therefore very restrictive when it comes to publishing materials data, and frequently basic information such as stiffness and Poisson’s ratio is missing.
9. Multimaterials

Multimaterials is a term for materials of different types that are joined together. An adhesive that can bind to several different materials is often an interesting alternative, as it can form a tight bond over the entire overlap area, spread load over large areas and keep the joining processes at moderate temperatures.

Still, the difference in thermal expansion between different materials can cause severe problems during production and when the product is used. The resulting dimensional changes mean that joints are exposed to additional loads that reduce their normal load-carrying ability. The strains that occur often result in deformation of the product. If the design is poor, the thermal loads can become high, with permanent defects a result.
9.1 Geometry and design

Apart from the differences in expansion between different materials and the level of temperature change, the product's overall geometry and the joints' local design have a major influence on how the whole product will behave. The problems are largest where one or both materials sections are stiff and the joint is long and straight. Fewer problems are encountered in products with curvature or with many short joints. In small and short adhesive joints, the effects of thermal “mismatch” may not occur.

Spot joining methods can allow a certain temporary “gap” in the structure during the curing cycle that does not lead to permanent geometrical changes, but the need for sealing remains. An elastic adhesive can in some cases allow a smaller “gap.”

9.2 Composite material

Glass and carbon fiber-reinforced composite materials with plastics as matrix material (GFRP, CFRP) are often joined to aluminium. Composite materials are special in the sense that the material only acquires its specific properties when the product is manufactured. The designer primarily tries to optimize the properties to meet the product’s needs. Similar materials therefore have different properties when they are built into different composites. For example, the fibers in a composite material have a surface treatment (sizing) that is tailored to the matrix material and which ensures good adhesion between the fibers and matrix.

In general, most of the heat-curing composite materials are relatively easy to bond. Many types of adhesives have good adhesion to the polymeric matrix materials. To get better adhesion, the surface of the composite can be pre-treated, e.g. by using laser, plasma, dry ice blasting or corona discharge.

Glass fibers have about a quarter of aluminium's temperature expansion, whereas carbon fibers basically do not have any thermal expansion at all (it can even be negative). The matrix material often has a linear thermal expansion which is 2 – 3 times higher than aluminium, which means that the matrix material itself often has a similar expansion coefficient to the adhesive.

The composite's expansion properties are dominated by the actual fiber directions. The fibers in one direction dominate the properties in this direction, while the matrix’s properties to a large extent determine the properties in the direction across the fibers. The content of fibers is of great importance here.

Stresses in the composite laminates between the matrix and fibers with their different directions, affect the geometry of the product. This becomes particularly clear if the product is exposed to adhesive-curing temperatures that are above the matrix material’s glass transition temperature (Tg). In this situation, an external load can cause large deformations of the product. The load can come from the joining of materials with different thermal expansions.

The risk of galvanic corrosion is another important aspect for the joining of aluminium and carbon fibers, as carbon fibers are electrically conductive and nobler than aluminium. With glass fiber fabrics as the outer layer of the laminate and adhesive bonding as joining method, the materials can be kept isolated from each other.
10. Occupational health and safety

Polymers or plastic materials can be divided into thermoplastics and thermosets.

In thermoplastics, the molecules form long chains that solidify at low temperature. Sometimes, they have crystalline features, but these remelt during heating.

In thermosets, small molecules react and form chains in a three-dimensional network. This reaction is not reversible and the network can resist substantial heating before breaking up into small molecules.
10.1 Health issues in production

Most adhesives, including epoxy, polyurethane and acrylic adhesives, are based on thermosets. Thermosets contain low-molecular polymers that are chemically reactive. Health effects then arise because these are small enough to get inside the body. Inside the body, these polymers can react and cause injuries.

Exposure to decomposition products from heating to high temperatures can also cause a health risk. Those who work with thermosets can primarily be affected by exposure in two ways: through the skin or through respiratory airways.

When selecting an epoxy or PUR adhesive, a high molecular weight is preferred from an occupational health point of view. Preferably, the molecular weight for an epoxy adhesive should exceed Mw>1000 and the isocyanate in the PUR adhesive should have as high a vapor pressure as possible or be pre-polymerized. It is not possible to make these adhesives completely harmless as this also means they will lose their function. The exposure risk can be minimized through the use of high-viscosity adhesives and automated processes, as well as by enclosed processes such as injection.

Information on possible health hazards and appropriate protection is documented in the safety data sheets that accompany the adhesive.

1. Contact dermatitis
The skin reddens and blisters where the uncured adhesive has been in contact with the skin (mainly epoxy adhesives). Initially, these reactions occur on the part of the skin which was in contact the adhesive, and once you’ve become sensitized, one can easily get a permanent hypersensitivity to the substance. Sensitized individuals may react very strongly to epoxy products without coming into direct physical contact with them.

2. Difficulty in breathing
The airways, bronchial tubes and pulmonary alveoli become irritated, which makes the bronchial tubes swell or the pulmonary alveoli fill with fluid, which creates a chemical pneumonia. These symptoms mainly occur with PUR adhesives, as uncured adhesives contain volatile isocyanates. The isocyanates can also be released when heating a cured PUR adhesive to over 200°C.
10.1.1 Designing the workplace
To minimize the risk of people who work with adhesives getting adhesive on their skin or breathing in hazardous substances, the process steps should be clearly described in writing and the workplace should be designed in such a way that contamination of staff and equipment is avoided. The staff should also be educated in the health risks and should know what to do if they are exposed.

- Clear routines that describe how to work with adhesives should be developed. This not only safeguards the working environment but increases the quality of the bonded product.
- Spillage should be taken care of immediately and disposed of close to where it occurred in ventilated waste containers.
- Exhausts and ventilation should be effective and there should be negative pressure at the adhesive station. This ensures that air pollutants do not spread to nearby premises.
- It should be possible to wash off any spillage adjacent to where the adhesive bonding takes place.
- The workplace should be provided with signs stating that adhesive work is in progress and which type of adhesive is in use.

10.1.2 Protective equipment
Appropriate protective equipment, adapted for the adhesive, should be used. Each person that may come into contact with the adhesives shall have appropriate personal protective equipment.

- One should be fully covered, preferably in a color that differs from the adhesive, so the adhesive is easily detected if it spills on the clothes.
- Gloves should be made of a material that is not permeable to harmful monomers.
- Safety goggles should protect the eyes from splashes of adhesive.
- If there is a risk of airborne substances such as isocyanates, protective face masks with the correct filter should be used.
- If possible, rings and watches, etc., should be removed, as the adhesive may end up underneath these and irritate the skin.
- Adhesive that has come into contact with the skin should be washed off with soap and water. Do not use solvents, as these dissolve the skin’s fat layer, which works as a barrier.
- Use a moisturizer so the skin is smooth and does not crack. This protects the skin from exposure into wounds and cracks.

Aerosols are formed during spraying. Aerosols and vaporized solvents are easily inhaled. There is therefore a need for well-ventilated spray booths. Even for immersion treatment, encasement and good ventilation are required. Manual work should be avoided.
10.1.3 Safety legislation
Because adhesives may pose a risk to both health and the environment, the use of adhesives is covered by each country’s own health and safety legislation.

10.2 Surface treatment
chemicals and primers

Surface treatment often involves the use of chemicals that can clearly be harmful for the people who come into contact with them. In order to use a surface treatment process, some form of facility is required and health, environment and safety issues must be taken into consideration as an integral part of the plant design. Established and standardized procedures are available.

Primers can be applied without advanced equipment, which can easily lead to carelessness and the overlooking of health risks. There is probably a greater health risk in the use of primers than adhesives. Primers resemble a very low viscosity adhesive. They usually contain low-molecular reactive binders, one or more different solvents, and more chemically active additives such as corrosion inhibitors and activators. A primer can therefore be a dangerous mix. Repeated skin contact with primed surfaces can also pose a health risk.
Appendix – Example checklist

1. Material 1
2. Material 2
3. Surface of material 1
4. Surface of material 2
5. Surface condition/cleanliness etc., material 1
6. Surface condition/cleanliness etc., material 2
7. Size of joint
8. Is visible adhesive outside the joint acceptable or not?
9. Preferred color of the adhesive
10. Except for mechanical joining, are there other functionalities to be achieved with the adhesive bond? These can include acoustics, sealing, electrical insulation and thermal conductivity
11. Will other kinds of joining be used together with the adhesive, such as welding, riveting, clinching or screwing?
12. Is dismantling for repairs and/or maintenance expected?
13. What is the expected life of the joint? (Months, years, decades)
14. What is the expected operational temperature for the joint?
   Min _____, Max _____, Typical _____
15. What kind of environment will the joint be exposed to?
   i. Indoor [ ]
   ii. Outdoor [ ]
   iii. UV exposure [ ]
   iv. Chemicals ________________
   v. Special corrosion requirements
16. Will further machining of the joint take place? (Cutting of long lengths into shorter segments, milling or grinding to correct dimensions)
17. Will the product, including the adhesive joint, be subject to surface treatment, such as powder coating or wet paint? What chemicals and temperatures will be involved in such surface treatment?
18. Mechanical properties (for instance preferred stiffness)
19. Load (size and type of load)
20. Will load be static or dynamic?
21. Curing (two-component, heat, UV, moisture)
22. Requirements on application techniques (automatic, tolerances)
23. Desired viscosity
24. Fixtures/guides to locate parts in the correct positions
25. How to achieve correct thickness of adhesive joint
26. How to handle excess adhesive
27. Need for temporary fixtures during curing
28. Environment, health and safety (risk assessments, waste handling, storage of dangerous products and waste, permissions from authorities)
29. Training of staff
30. Quality control and documentation
The information, advice and comments in this manual are based on data gathered from a number of different sources. The data was judged to be correct at the time of printing. However, Hydro accepts no liability whatsoever for the correctness and/or completeness of the details in this manual. Hydro reserves the right to alter technical specifications.

Editor: Kevin Widlic, Hydro
Design and layout: Mads Pedersen, Artbox.no
Hydro is a leading industrial company that builds businesses and partnerships for a more sustainable future. We develop industries that matter to people and society. Since 1905, Hydro has turned natural resources into valuable products for people and businesses, creating a safe and secure workplace for our 34,000 employees in more than 140 locations and 40 countries. Today, we own and operate various businesses and have investments with a base in sustainable industries. Hydro is through its businesses present in a broad range of market segments for aluminium, energy, metal recycling, renewables and batteries, offering a unique wealth of knowledge and competence. Hydro is committed to leading the way towards a more sustainable future, creating more viable societies by developing natural resources into products and solutions in innovative and efficient ways.