Fundamentals
M7
MAINTENANCE PRACTICES

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M7.15
Welding, Brazing, Soldering and Bonding

EASA Part-66
CAT B1

Training Manual

Lufthansa Technical Training

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M7 MAINTENANCE PRACTICES

M7.15 WELDING, BRAZING, SOLDERING AND BONDING

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SOLDERING METHODS

Soldering

SOLDERING OF METALS

General

Soldering and fusion welding are related procedures in order to connect metallic work pieces.

In both cases the space between two metallic work pieces is filled with a completely or partially melted metal or metal alloy. Work piece and filler metal are heated to a minimum temperature. This is why these procedures are called thermal connection processes.

In both cases the parts cannot be separated without destroying the weld or the work piece. This procedure is therefore called „inter–crystalline connection“.

Differences between Soldering and Welding

When fusion welding, the melt-areas of the filler metal and the work piece are almost or completely identical. When soldering, the filler metal will melt at lower temperatures than the work piece.

Whilst welding, the connection is affected due to the hardening of the mixture of the filler metal and the melted portions of the work pieces which are to be combined. When soldering, the connection is realized due to the hardening of the solder, which causes a connection with the unmelted parent metal by way of diffusion processes and alloy processes.

Basic Procedure of Soldering

A soldering joint is done by filling a gap between two parts (base material) with a melted metal (solder). Thereby a small alloy zone at the surfaces of the base material does occur due to diffusion processes at the boundary layers.

The solder does not always have to be added when soldering; In some cases it will be created from the work pieces to be soldered.

The bonding mechanism created during soldering is metallic and forms a firmly bonded connection.

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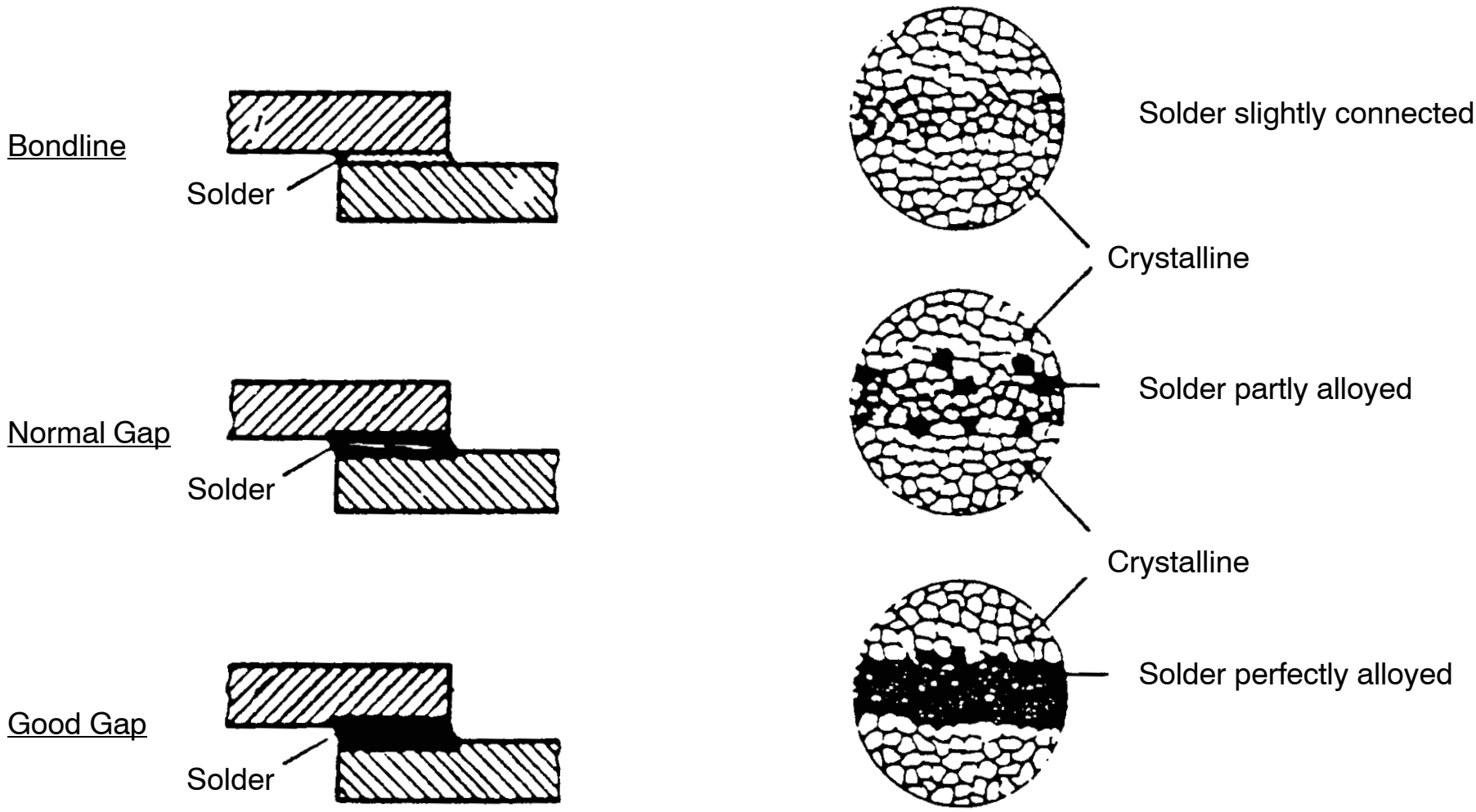


Figure 1 Brazing/Soldering General

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INFLUENCE OF SOLDERING TEMPERATURE

General

The lowest temperature that must exist at the contact area of solder and work piece in order to let the solder flow and adhere to the parent metal is called the operating temperature.

The operating temperature depends exclusively on the properties of the solder (which are caused by the composition of the solder alloy), but not on the amount of solder or the properties of the parent metal.

This makes it a temperature valid and characteristic for all soldering processes.

Usually the work pieces to be soldered are heated to a temperature above the operating temperature. The permitted temperature may vary within a certain range. This range has its lower limit at the operating temperature and its upper limit at the maximum soldering temperature.

The maximum soldering temperature is the temperature above which the following damage is caused:

- elements of the solder alloy will evaporate
- the work piece will soften
- the work piece will get coarse
- important components of the flux will evaporate.

The range of the permitted soldering temperature decreases with the sensitivity of the material.

Capillary Action

Liquid solder has, like water, the characteristic to be sucked into small gaps. This characteristic is called capillary action.

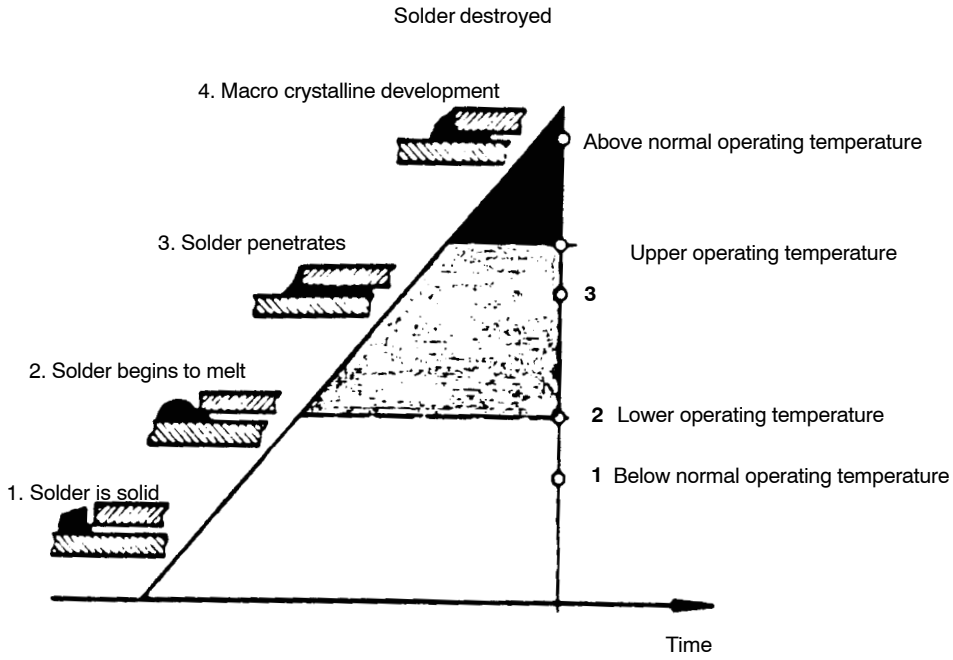
Satisfactory soldering depends not only on the flow of the solder but also on the capillary action of the solder and the soldering gap of the material.

There is a direct connection between the solder’s capillary head and the soldering gap: the smaller the gap is the higher is the capillary head.

Therefore the gaps noted in working sheets must always be adhered.

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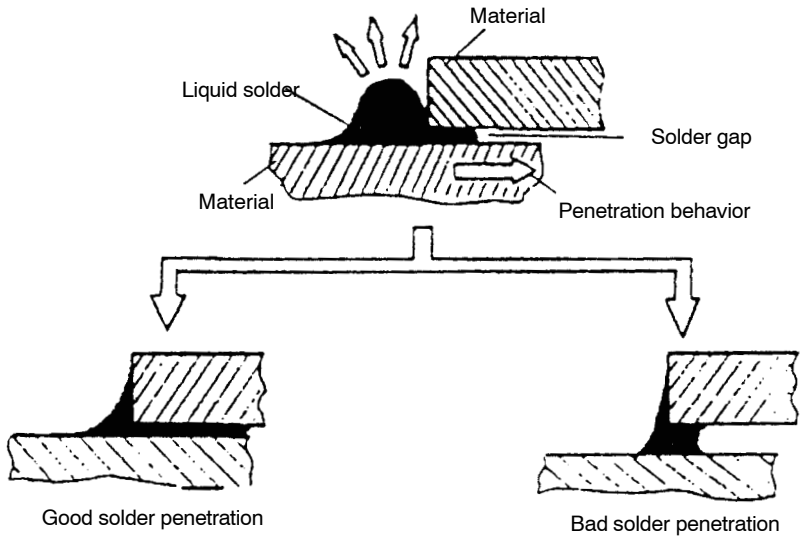


Figure 2 Brazing/Soldering Process

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SOLDERING GAP

General

A correctly conducted soldering gap has a huge influence on the soldering joint quality. Only if the gap is correctly adjusted the solder can fill the whole gap completely.

Soldering Gap Width

In normal cases the soldering gap is designed as a very thin gap with a width of 0.05 to 0.5mm. This gap is then completely filled by the solder due to capillary force.

The capillary forces cause, if the environment is optimal (e.g. optimal temperature, oxide-free/clean surface and, if necessary, the aid of flux), a rising of the solder against gravity.

Wider gaps than 0.5mm have only to be chosen in exceptional cases, e.g. if the displacement of the flux in a narrower gap could cause problems.

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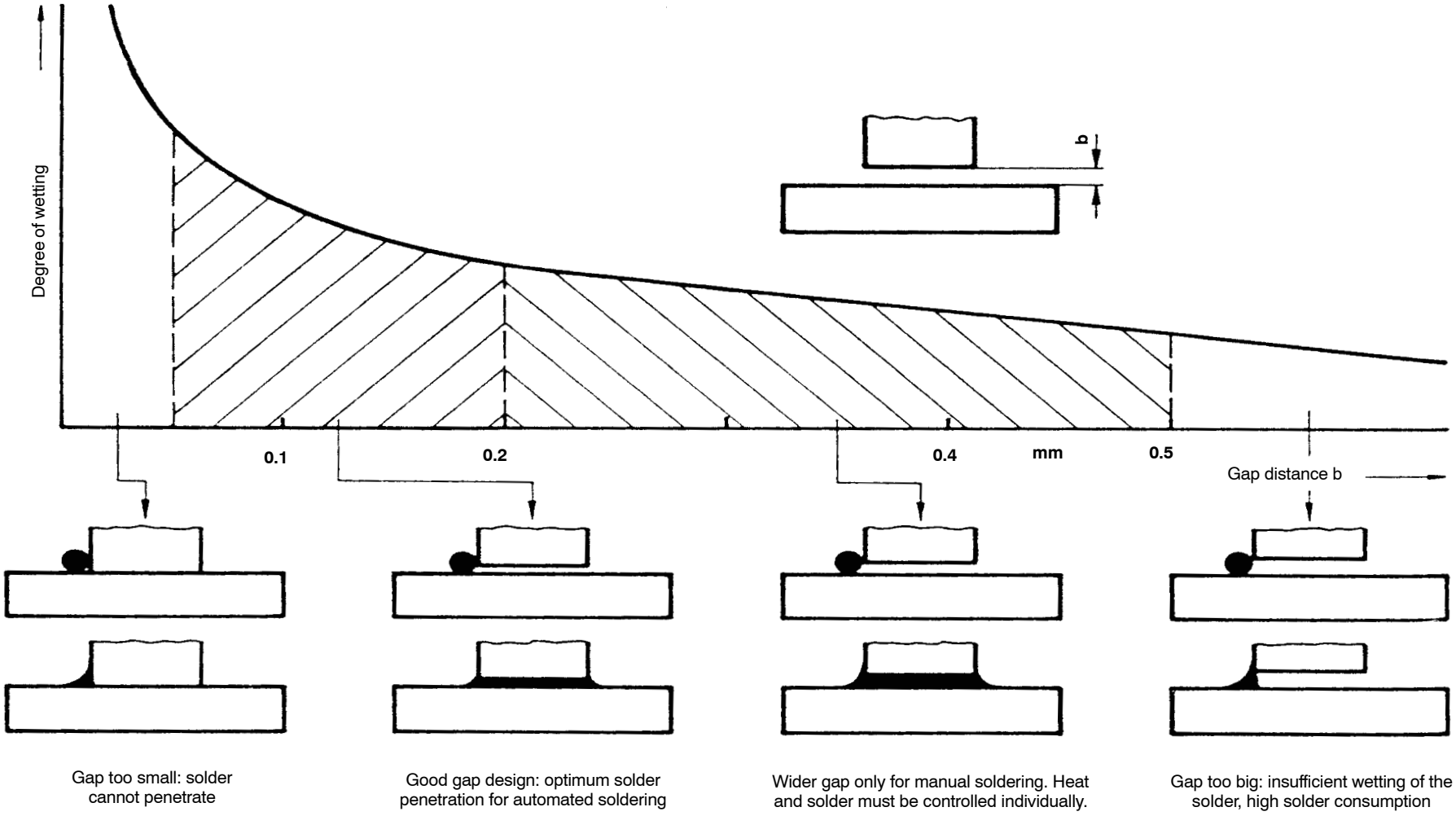


Figure 3 Soldering Process (cont.)

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Soldering methods

Soft Soldering, Brazing/Brazing with High Temperature Solder

Both soldering types are differentiated due to their working temperature (T_A).

Soft soldering (T_A < 450˚C) only results in low-strength joints. Hard soldering (T_A > 450˚C) makes it possible to transmit the high forces in mechanical designs without damaging the solder joint.

The soldering methods are classified due to their soldering temperature as follows:

- Soft soldering: T_A < 450˚C
- Brazing: T_A > 450˚C for „normal solder material“
- T_A > 950˚C for high temperature solder material

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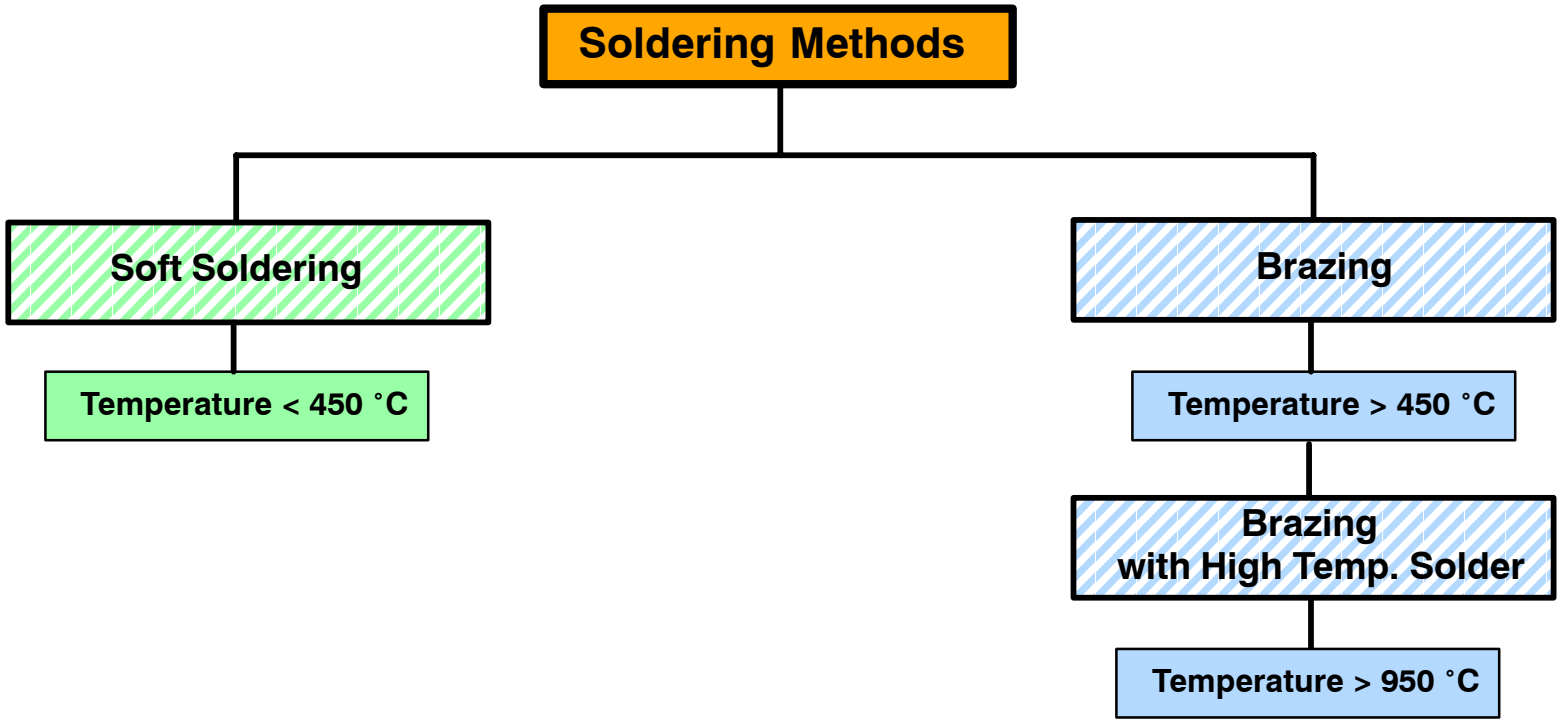


Figure 4 Soldering Methods General

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SOFT SOLDERING

General

The working temperature T_A during soft soldering is below 450˚C and only results in low-strength joints.

Soft soldering is applied in:

- Tool building
- Apparatus construction
- Bodywork
- Plumbing
- Electric and electronic

The main application area of soft soldering is the connection of non-hot metallic and thus electrically conducting copper parts in electronic technology.

The main reason is that copper has a outstanding soldering ability due to the solvability of its oxides and its good ability to form alloys with tin.

Tin on the other hand is the base metal in most of the solders.

Soft Solders

Soft solders are mainly tin-lead alloys, which solidify at less than 183˚C.

The mixture of soft solders for the electronic industry is between Sn-levels of 50 to 70%.

For bodywork tasks or in the plumbing areas low-tin solders with a SN-level of ca. 30% are used.

In the food industry low-lead solders are compulsory; the Sn-level is ca. 90%.

Flux for Soft Soldering

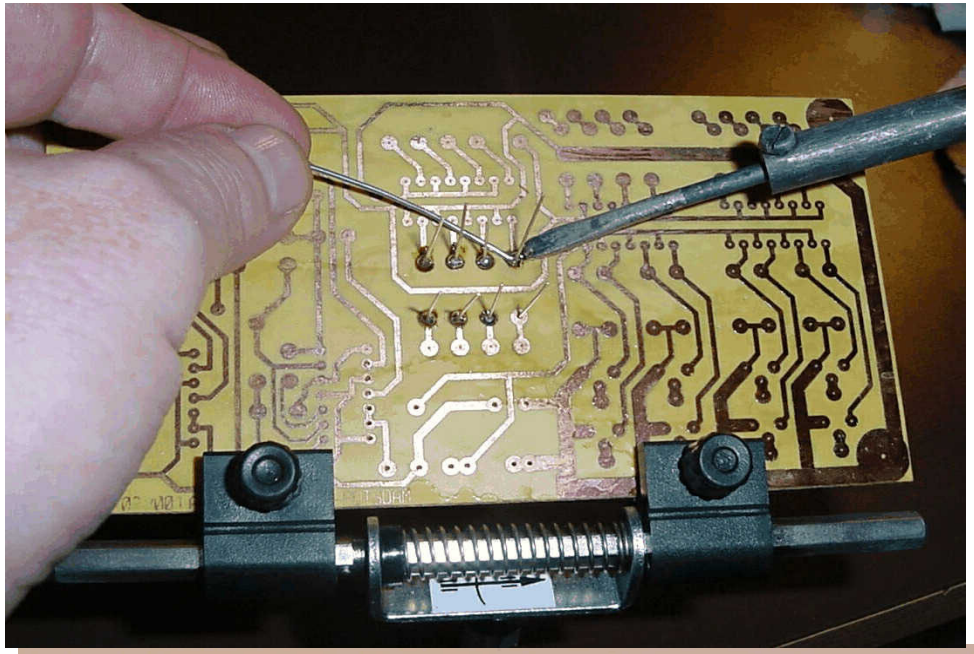
$ZnCl_2$ and/or Solutions containing NH_4Cl or pastes plus colophon (a nature product containing resin acid) are used as a flux in solid or liquid form.

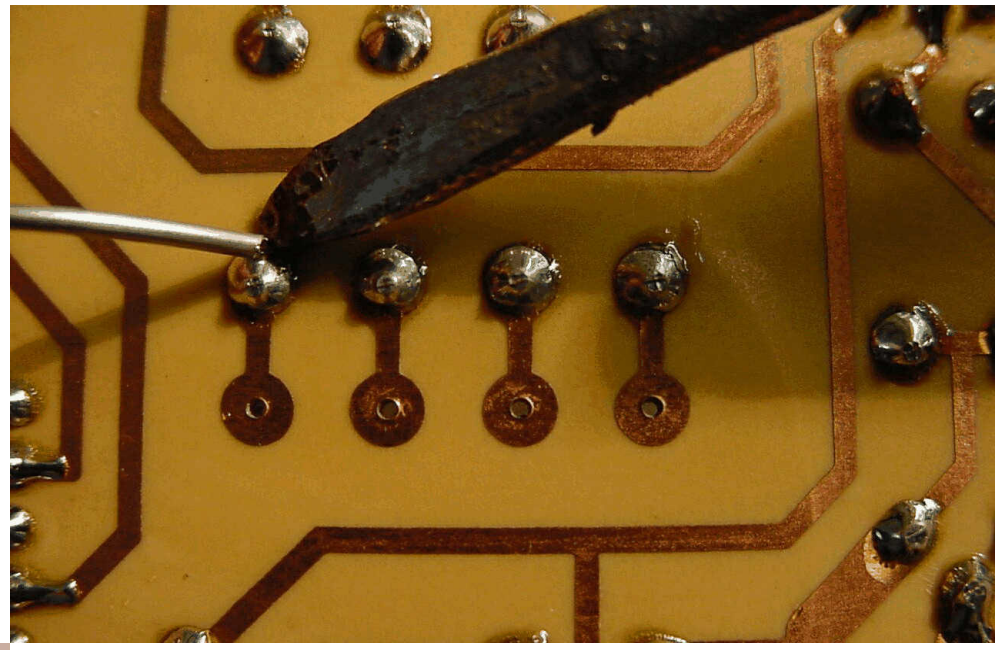
The chloritic fluxes have very good oxide-solving characteristics, but the residua are corrosive and have generally to be removed with hot aqueous solutions.

Colophon is a weaker flux and thus an intensive pre-cleaning of the joining surfaces is needed. But it does not leave corrosive residua and is therefore essential in electronic technology.

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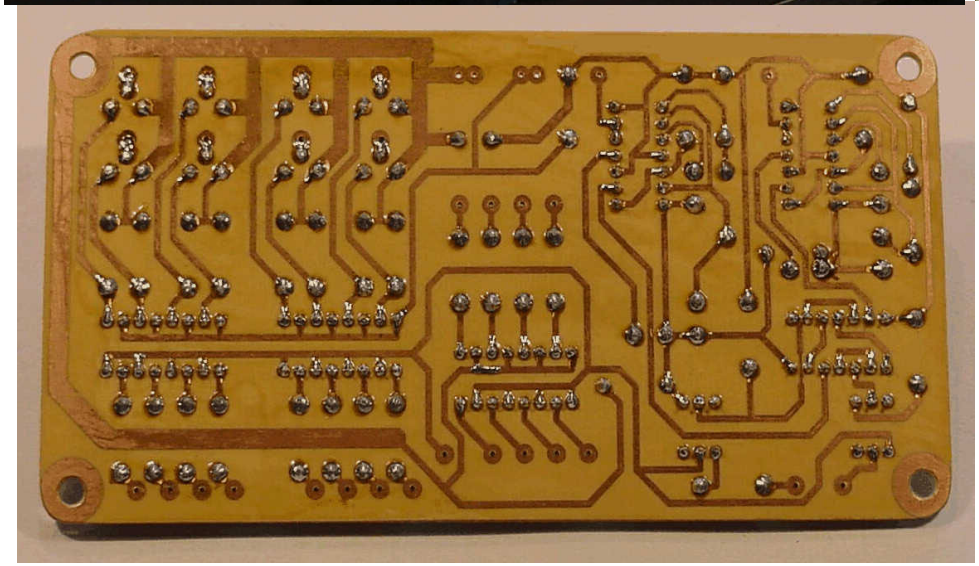




Figure 5 Soft Soldering

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INSPECTION OF SOLDERED JOINTS

Solders

General Requirements

A metal or an alloy which is to be used as solder for soldering must have the following properties:

- the ability to form a good solid contact with the parent metal used
- it must melt and flow easily to ensure the distribution of the solder via capillary action
- its composition must be homogeneous and stable to prevent the separation of solid and fluid parts whilst soldering
- the ability to provide soldering that meets various requirements such as stability and corrosion resistance
- depending on the requirements, it must be able to prevent or bring about a reaction between the solder and the parent metal.

SOLDER CATEGORIES

Aluminium-Silicon Solders

These are suitable for aluminium and aluminium alloys and can be used for cast metals and masticated materials. They can only be used with flux. The flux can usually be removed in boiling water.

Copper-Phosphate Solders

These solders should primarily be used for soldering copper and copper alloys. To a limited extent they are used for silver, tungsten and molybdenum.

They should not be used for iron or nickel-base-alloy nor for copper-nickel alloys with a nickel content of more than 10%.

When used for copper, flux is not necessary. For all other materials, including copper alloys, flux is needed.

Silver Solders

Suitable for most ferrous or non-ferrous metals with the exceptions of aluminium and magnesium. The use of flux is generally necessary.

Gold Solders

These are designed for soldering iron-, nickel- and cobalt-base materials which have to be oxidation- and corrosion-resistant. Due to their small influence on the parent metal they are usually used for thin parent material.

They are used together with a borax-boric acid flux.

Copper Solders

These solders are suitable for different ferrous and non-ferrous metals.

Copper Zinc Solders

They are used for the same materials as copper solders, but their corrosion resistance when soldering copper, silicon-bronze, copper-nickel alloys and corrosion resistant steel is not sufficient.

Magnesium Solders

Are usable for soldering magnesium-base alloys. Heating has to be controlled carefully to prevent melting of the parent metal.

Nickel Solders

Generally used because of their good corrosion- and heat-resistance.

Mainly used for soldering corrosion-resistant steel, nickel and nickel-base alloys. They can also be used for carbon-steels, ferrous alloy steels and copper. They are heat-resistant up to about 980° C.

Cobalt Solders

The special field of usage are cobalt alloys. Cobalt solders have an especially high heat resistance up to a maximum of 1150° C.

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Figure 6 Solders

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Flux

General

Fluxes are aqueous or alkaline solvents or pastes, which contain acid or other substances which separate acid substances when achieving the soldering temperature.

Borax acid is used as the acid; the acid substances, which are separated from the substances, are boride, chloride, fluoride or colophon.

The melting point of the flux must be lower than the melting point of the solder.

Some solders (like lithium or the copper-phosphor solders) can act themselves as flux when used with certain alloys.

The melting of the flux can also be used as temperature indication at the soldering area.

Metallic Oxidation

When base metals are subjected to air, chemical reactions will take place. Higher temperatures will speed up these reactions. The main reaction is oxidation, but the forming of nitrates and carbides is possible.

The speed of oxidation and the structure of the oxides vary according to the composition of the material. In almost all cases the presence of oxides will prevent satisfactory soldering.

Function of Flux

When soldering, flux is used to remove or dissolve unwanted oxides or residues or to react with them. Otherwise the soldering would be impaired or prevented.

Since the flux must be displaced by the liquid solder easily, the viscosity of the flux is very important.

Under certain conditions the flux must also prevent the evaporation of certain constituents of the solder.

Thus the flux supports the melting and bonding process of solder and base material during the soldering process.

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Figure 7 Flux

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Inspection of Soldered Joints

General

Visually inspect the soldered joints for any gritty or jagged joint surfaces and for traces of flux.

Inspection of Surface Quality

Solder connections should be smooth, shiny, and uniform in appearance. Also look after a good contact of the solder to the part's surface

Any soldered joints that look questionable should be de-soldered, cleaned if needed, flux and other possible residua removed and at last re–soldered.

Inspection on Flux Residua and Cleaning

After completing the soldering operation, it is imperative that all traces of residual flux be completely removed.

This is especially important, since the flux is attacking the part's surface.

Thoroughly clean the entire installation area with generously applied solvent and a soft–bristled brush. Clean the solder connection area until no visible signs of residual flux remain, and blot the area dry with a clean gauze sponge .

Normally no visible flux residua must remain at the soldering area.

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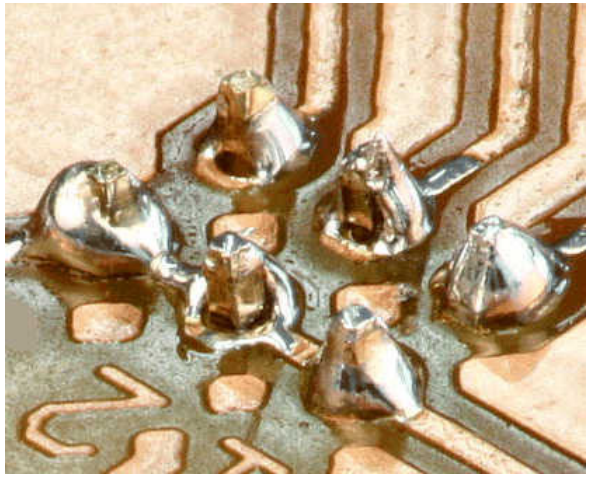
Crackes in Soldering



Cold Soldering



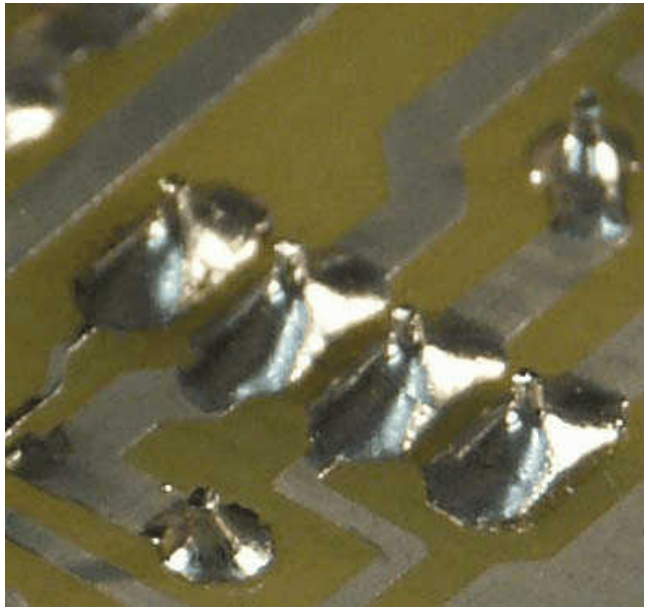
Cold Soldering



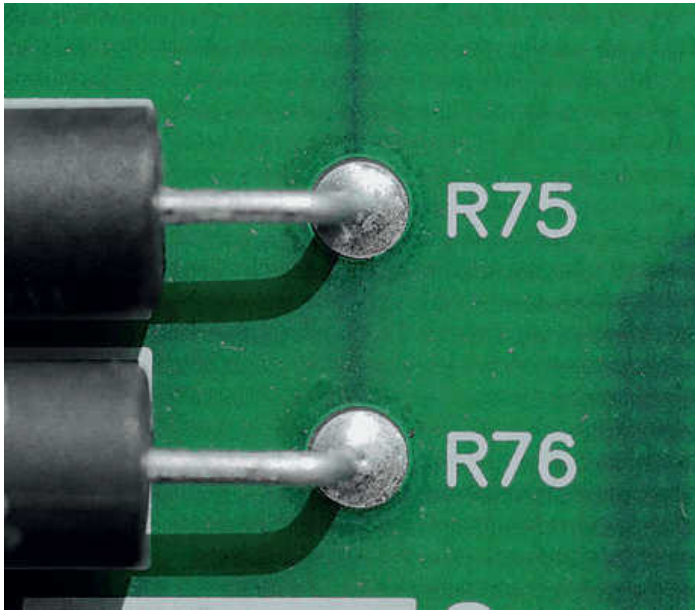
Cold Soldering



Flux Remover



Correct and smooth Soldering



Correct and smooth Soldering

Figure 8 Inspection of Soldered Joints

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BRAZING METHODS

Brazing

General

Brazing can produce soldering joints with a higher strength than the basic material has.

The basic material is mostly steel, copper, nickel and titan.

Every brazing methods have a melting temperature of the solder above 450°C in common. But the temperature is below the melting temperature of the basic material of the parts to be soldered.

Brazing General

Brazing can be done either by hand or mechanical with burner or in special soldering machines with induction or resistance heating.

In most of the cases continuous furnaces or chamber furnaces are used in which a shielding gas atmosphere or a vacuum is present.

Due to the high quality standards in the aircraft industry especially for easy reacting titan parts a shielding gas atmosphere is essential.

Due to the shielding gas or the vacuum the surface oxides are degrading; thus in furnace brazing a flux is often not needed.

A disadvantage in comparison to induction brazing is that not only the soldering surfaces but the whole part must be heated up to the soldering temperature.

Brazing processes are usually named according to their type of heating. The following processes are of current industrial importance:

- flame brazing
- furnace brazing
- induction brazing
- resistance brazing
- dip brazing
- infrared brazing.

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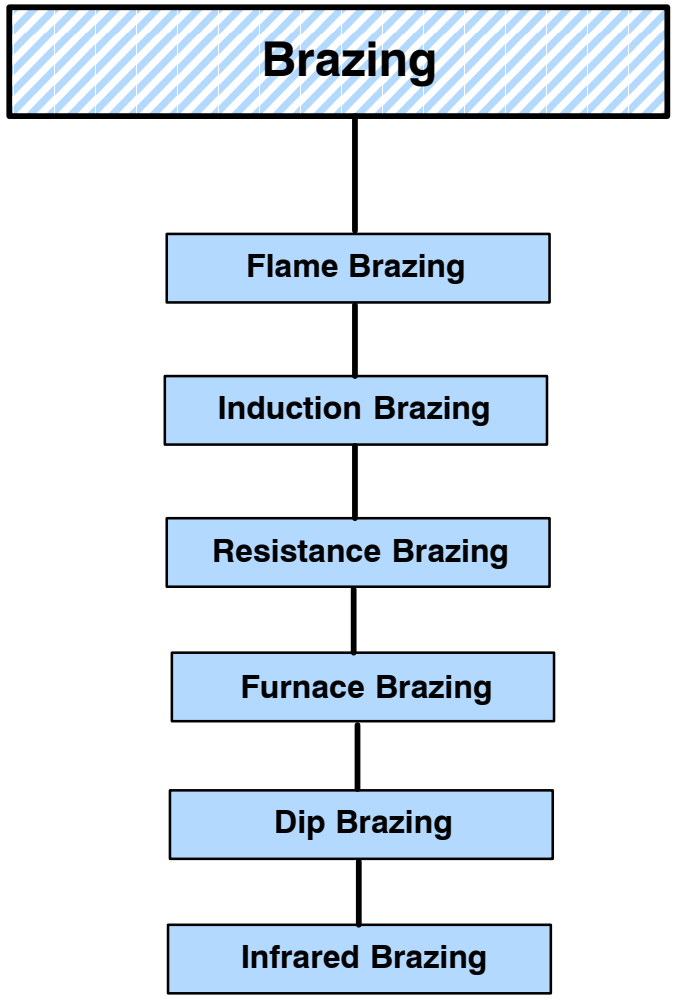


Figure 9 Brazing Methods

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BRAZING PROCESSES

Flame Brazing

Heating is caused by one or more gas burners, which can be used either manually or mechanically.

Depending on the required temperature and the amount of heat necessary to reach it, different gases such as Acetylene and Propane are used.

These are burnt together with air, pressurized air or oxygen.

The solder is either added before the burning procedure (in the form of rings, slices, strips or powder) or it is added manually (as wire or in the form of a bar).

The use of flux is necessary.



Figure 10 Flame Brazing

Induction Brazing

In this process, the heat required for brazing is created by induced currents. The work piece is placed near a coil which is connected to alternate current. Thus the work piece becomes part of the electrical circuit.

The currents which are induced in the work piece create heat because of the electrical resistance of the material. The surrounding area remains cold except for the radiation heat.

For the brazing of small components, high frequency installations of 450 - 2000 kHz are usually used. Their power is mostly between 1 and 15 KW.

Medium frequency of about 5 to 10 KHz is preferably used for larger components. In this case, the power is usually between 5 and 10 KW.

The material strength at the soldering area is very important here.

The heating of the soldering area is effected without contact by water-cooled induction coils.

Because of the fast heating of the soldering area, the solder is often applied before the soldering starts.

If protective gas is not used, the work is performed with the help of flux.

Protective gas soldering is either performed in a room filled with protective gas, or by using an induction coil with integrated protective gas nozzle. The latter shields the soldering area locally because of the escaping protective gas.



Figure 11 Induction Hard Brazing

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BRAZING METHODS (CONT'D)

Resistance Brazing

The heat necessary for this soldering is created by the electrical resistance of the soldering area in the electrical circuit. The parts to be soldered are held in place with sufficient pressure by two water-cooled electrodes.

These can be made of coal, graphite, copper or copper alloy, depending on the required electrical conductivity. The use of resistance welding machines is possible.

Furnace Brazing

Furnace Brazing is preferably used when the parts to be connected can be pre-assembled. The solder is added as wire, rings, foils powder or paste. Furnace brazing can only be carried out without flux in a special atmosphere that that takes over the function of the flux.

Furnace brazing is often performed in a reduced gas atmosphere such as hydrogen. To create a special, neutral atmosphere, pure dry inert gases such as argon or helium are used. These inert gases are very unreactive and chemically indifferent.

A great amount of furnace brazing is performed in a vacuum. This prevents oxidation and, under certain conditions, the use of flux is unnecessary. This procedure is of high importance in aviation, astronautics and nuclear energy techniques, either because highly reactive materials are used here or the use of flux is not permitted. The vacuum is maintained by continuous pumping and removes evaporating substances which are created during the soldering process.

The vacuum-furnace brazing is a relatively economical procedure to use an exactly controlled furnace atmosphere. The vacuum creates the cleanliness of the surface which is necessary for a good contact of work piece and solder and the flow of the solder without use of flux.

Material containing chromium or silicon can be soldered very well in a vacuum. Without using the vacuum, a very clean atmosphere is required with a very low point of condensation. Furnace soldering in a vacuum is usually used at temperatures higher than 900˚C and as a rule guarantees relatively high grade soldering connections.



Figure 12 Resistance Brazing Machine



Figure 13 Furnace Brazing Machine

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BRAZING METHODS (CONT'D)

Dip Brazing

Dip brazing can be performed in two different ways:

- as salt bath soldering. In this case the solder and flux have already been applied to the soldering area. The electrically-heated salt bath only supplies the heat necessary for the soldering process.
- as metal bath soldering. The metal bath consists of molten solder. The cleaned parts are dipped into the solder after they have been treated with flux. This soldering process is only applicable to small parts.



Figure 14 Dip Brazing Station

Infrared Brazing

This procedure has gained economical importance since strong quartz-lights have been developed. These quartz-lights (commercially available up to 5KW) are used as heat sources for the soldering process.

The use in an extreme low- pressure atmosphere or in a protective gas atmosphere is possible.



Figure 15 Infrared Brazing Station

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Reaction of Materials to Soldering

General

Some metals and alloys react to being soldered which impairs the soldering and sometimes call for special action. Some of these reactions are caused by the material (carbide precipitation, oxidation, hydrogen embrittlement, sulphur embrittlement, etc.), whilst others are caused by the solder (vapor pressure).

Others again are caused by material and solder (phosphoric embrittlement, stress cracking).

Carbide Precipitation

Corrosion resistant steel and some alloys which contain chromium and carbon tend to carbide precipitation at temperatures 427–816° C.

The carbon content of the material reacts preferably with the chromium and is precipitated as chromium-carbide.

The parent metal which is thus reduced in its chromium content will lose its corrosion resistance.

The precipitated carbides can be dissolved again by a heat treatment between 1010 and 1120° C, followed by rapid cooling.

A heat treatment of 2 hours at 870° C, followed by a furnace cooling to 538° C and subsequent air cooling can spread the chromium that has not yet been precipitated evenly in the material again.

The carbide precipitation will not exceed acceptable limits with normal corrosion resistant steels, as long as the soldering is carried out quickly.

Oxidation

Some oxides are easy to remove, but chromium, titanium, silicon, manganese and beryllium form oxides which are hard to remove. This is why alloys containing these elements require special procedures.

Chromium oxide can be removed with some fluxes containing fluorine.

Aluminium-, titanium-, silicon-, manganese- and byrillium-oxide can also be removed by special fluxes.

In many high temperature soldering processes where age-hardening alloys with chromium and aluminium are processed, very stable oxides are created, which are difficult to reduce. Such soldering should take place in hydrogen, helium, argon or in a vacuum. A galvanic nickel-plating can prevent the build-up of oxides due to its masking effect.

Hydrogen Embrittlement

Because of the small size of its molecules, hydrogen has the ability to enter many metals (diffusion).

The rate of diffusion rises with the temperature. When hydrogen enters material which is not completely oxide-free, it can reduce the oxide of the metal, provided the temperature is high enough.

Because the size of the molecules of the water vapor prevents them from diffusing to the surface, pressure is created in the material. In the case of copper this pressure can reach 63.3 N/cm^2.

These enormous pressures tear the material apart at its grain boundaries. Copper, silver and palladium which contain oxygen are especially endangered.

The hydrogen embrittlement of steel follows a different pattern. No water is formed, but the hydrogen atoms transform into hydrogen molecules at the grain boundaries and in the areas of non-metallic enclosures. Since the molecules are less mobile than the atoms, the removal of the hydrogen is thus more difficult. Heat treatment 90 - 200 °C or a long storage time can restore the toughness of the material.

Some materials cannot be soldered in a hydrogen atmosphere, because they would develop permanent embrittlement. Typical examples are titanium, zircons and their alloys.

Tantalum and niobium (or colombium) also show embrittlement when in contact with hydrogen, but their toughness can be restored by heat treatment.

Most other metals and alloys whose oxides can be reduced in a hydrogen surrounding have a surplus of elements that decrease the amount of oxides. These metals are not subject to hydrogen embrittlement.

Areas Subjected to Heat

The heat that is required for the soldering process can lead to softening of materials whose mechanical properties were achieved by cold-working. If the soldering temperature is higher than the recrystallizing temperature, a coarsening of the grains can be the result. Properties that were achieved by heat treatment can be altered.

The size of the area subjected to heat depends on the hard-soldering procedure. In general it is larger and less defined than in welding processes.

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Sulphur Embrittlement

Nickel and certain nickel alloys can be subject to embrittlement if they are heated in the presence of sulphur or substances containing sulphur.

Particularly at grain boundaries, nickel sulfide with a low melting-point is formed, which is soft and brittle and will break under load. Material damaged in this way cannot be regenerated. This is why it is important that nickel and nickel alloys are clean and free of sulfuric substances (oils, grease, paint, markings from color pencils etc.) before heating. the heating has to take place in a sulphur-free atmosphere.

Phosphoric Embrittlement

Phosphor builds brittle phosphides with many metals. This is why copper-phosphor solders are normally not used for iron alloys or nickel alloys.

Vapor Pressure

If soldering is to take place in a vacuum, care must be taken with selection of the solder. Solders containing cadmium or zinc cannot be used.

The reaction of solder and parent metal is important for the behavior of a soldering connection. The extent of these reactions depends on the composition of the solder, the parent metal and the heat treatment process.

Vacuum soldering takes place between 10^{-1} Torr and 10^{-4} Torr at temperatures up to 1200°C.

Since the vacuum removes all gases from the soldering area, you need not clean any gases which otherwise would have to be added. The intensity of the vacuum depends on the parent metal and the solder.

Certain oxides of the parent metal will disintegrate in the vacuum at soldering temperatures.

Difficulties because of contamination of the surfaces to be soldered caused by degassing of the parent metal are negligible in the vacuum.

The negative pressure around the parent metal and the solder will remove gases and evaporating contamination at higher temperatures. In some cases the properties of the parent metal are even improved.

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WELDING METHODS

Welding

General

Welding consists of joining two or more pieces of metal by applying heat or pressure with or without filler material. The necessary heat energy is applied from the outside.

Common sources of heat are:

- Electric current
- Chemical reaction
- Effects of beams
- Friction

Welding is a substance-to-substance joining, which can only be separated by destructive actions like mechanical or thermal cutting. It is differed between pressure welding and fusion welding.

Welding consumables, like e.g. shielding gases, welding flux or pastes are used as aids during welding.

Shielding Gases

Shielding gases are used for the protection of arc, material transfer and melted weld against the harmful effects of the surrounding atmosphere. It is differed between inert and active gases, which are sometimes used as a mixture.

Inert gases, e.g.:

- Argon
- Helium
- Nitrogen

Active gases, e.g.:

- Hydrogen
- Carbon dioxide
- Oxygen

Mixtures, e.g.:

- Argon-Helium (e.g. Varigon He30)
- Argon-Carbon-Dioxide (e.g.. Corgon18)

Explanation

- Inert gases: sluggish in reaction (*inert*), with low participation in reactions.
- Active gases: reactive, with high participation in reactions.
- Varigon, Corgon: Trademarks of the Linde Gas Company

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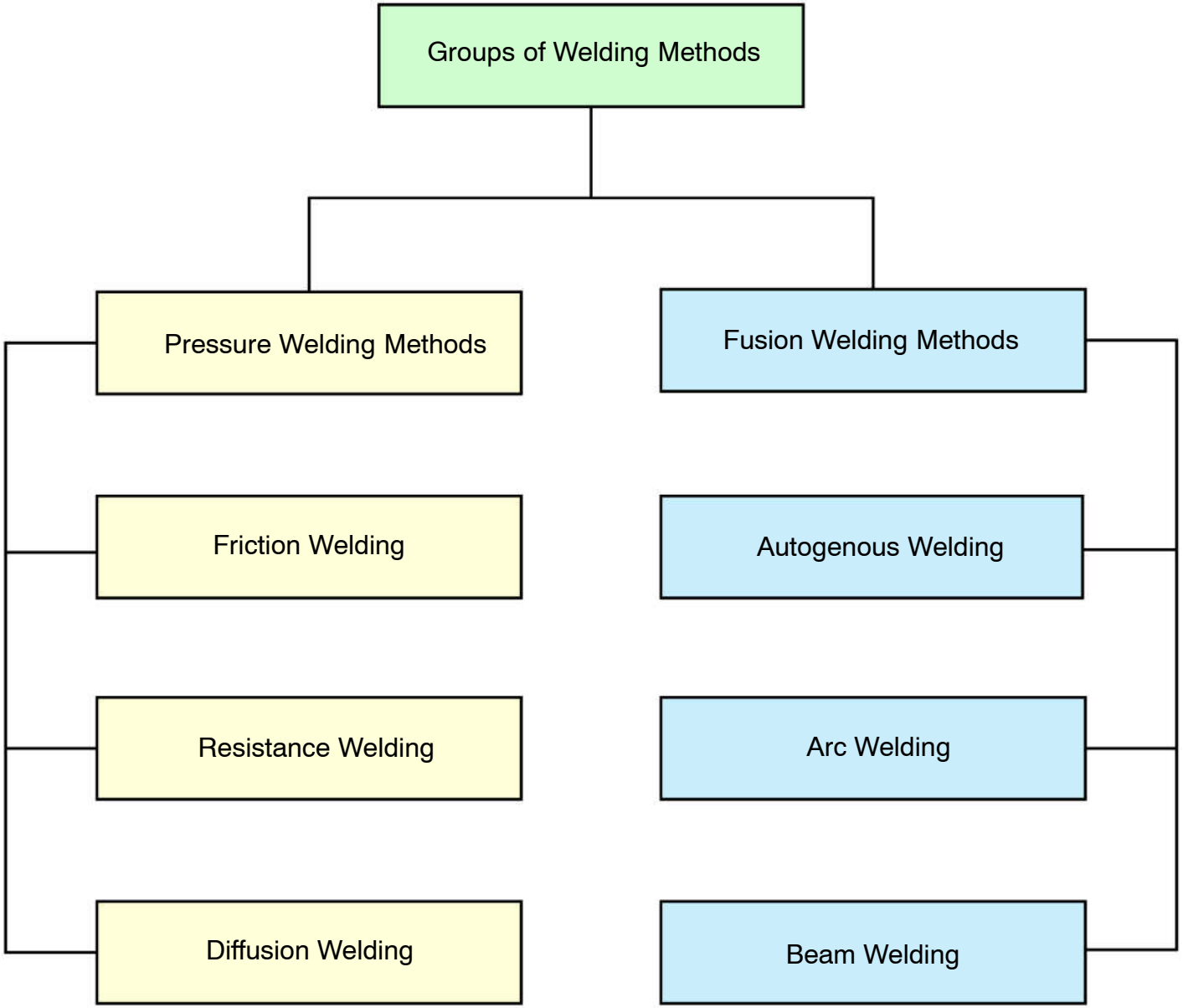


Figure 16 Overview Welding Methods

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Welding Preparations

Prior to the actual welding, the parts must be prepared for the process. The goal is to create, besides a high quality weld, a joint with low stress and deformation. Thus the following factors affect the welding and should so be taken into account prior to welding.

Influence Factors

Preparation:

- Cleaning of parts
- Selection of welding method
- Selection of welding consumable
- Selection of type of joint and edge form
- Stapling and if needed preheating of parts

Working phases:

- Heat Input
- Heat direction
- Welding Sequence

Finishing of welding joints:

- Heat treatment
- Turning
- Grinding
- Bating

Weld Quality

In order to create a good weld quality, besides a high quality conduction of the welding also the joining surfaces of the parts must be metallic bright. This means free from oil, grease, paint, oxides and other pollution. The welding consumable (welding wire) must be chosen depending on the material of the parts.

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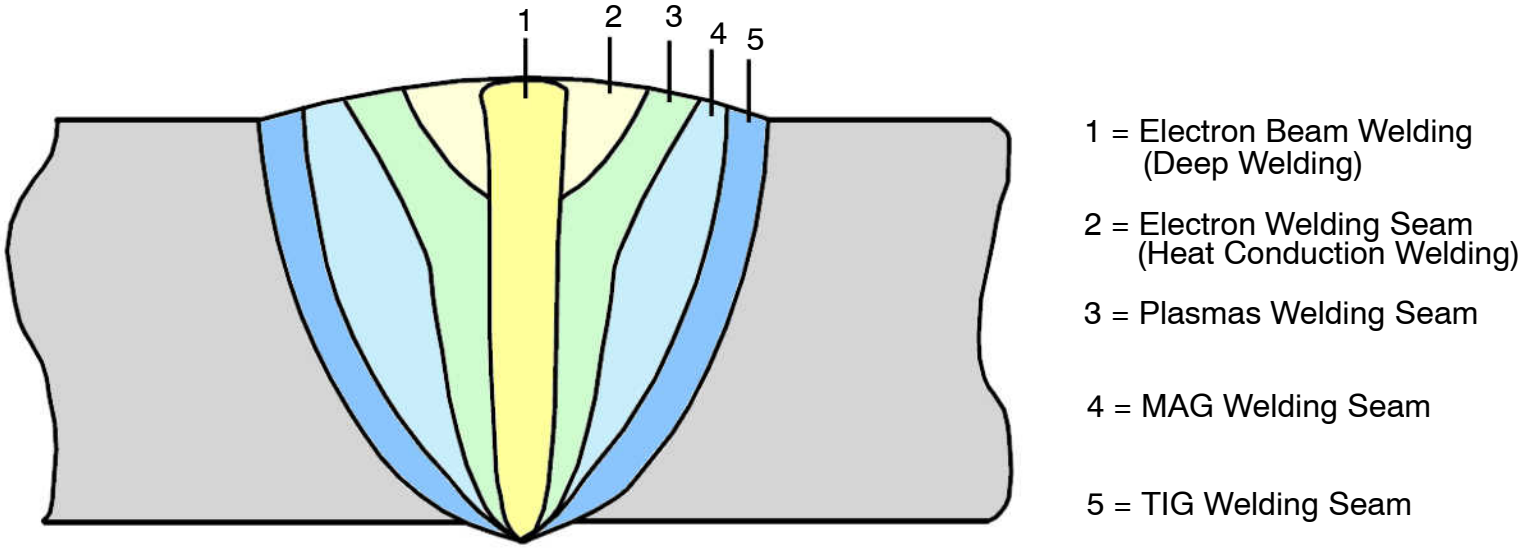


Figure 17 Comparison of Weld Sections

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Beam Welding Methods

GMAW-WELDING (MIG-/MAG-WELDING)

General

GMAW welding with the subtypes metal-inert-gas welding and metal-active-gas welding is a welding method in which an arc from the electrode to the part is present in a shielding gas atmosphere. The electrode is a welding wire (welding consumable) that comes from a coil and is fed by wire transmission wheels to the output nozzle.

The shielding gas, e.g. Argon or Corgon18 is flowing out of a concentric nozzle around the electrode and protects the arc, the transmitted drops and the weld pool against unwanted reactions with the surrounding atmosphere.

The MIG-/MAG welding method is a direct current method in which the electrode is the positive pole and the part the negative pole.

Emergence of the Welding Arc

The ignition of the arc is happening by a contact between electrode and part. After ignition the electrode must not be pushed back from the parts surface. The arc is burning itself automatically clean due to the high current density. A slow feed of the wire electrode to the surface supports the cleaning and is realized in modern MIG/MAG welding machines by a electronically controlled wire feed.

Application

The MIG-/MAG welding method is commonly used due to its mobility and simplicity. Besides the manual welding this method can also be used in a automatic manufacturing process (vehicle construction, machine construction etc.).

Materials

It is applicable for welding non-alloy and low alloy steels, aluminium/-alloys, nickel/-alloys, Copper/-alloys, inconel, monel and hastelloy. In build-up welding also silicon, tin and aluminium bronze can be treated.

Welding of titan, titan alloys and magnesium is in development.

Material Thickness

The thickness that can be welded start at:

- ca.0.7 mm for plain steel
- ca.1.0 mm for CRES and aluminium/-alloys
- ca.1.5 mm for nickel/-alloys
- ca.5.0 mm for copper

The upward thickness is nearly unlimited. Sheets with a thickness of 50 mm can be welded with the MAG process.

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Figure 18 MIG-MAG

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TIG WELDING

General

The main attribute of TIG (tungsten inert gas) or GTAW (gas tungsten arc welding) is the usage of a non-melting tungsten electrode and a inert shielding gas like argon or helium. TIG welding can be done with or without the help of welding consumables. In this method a arc is lightning between the non-melting electrode, which is surrounded by the shielding gas (e.g. argon), and the part's surface. The generated temperatures (3500–4200°C) are higher than the melting point of metals. The part's edges are melting, flow into each other and solidify without pressure to the weld. In order to fill the grooves or to build-up material welding consumable can be applied to the weld pool. This can be done manually or automatically.

Generation of the Arc

An arc ignition without contact is preferred since this preserves the electrode and prohibits tungsten inclusions at the ignition point. In newer TIG machines high voltage ignition impulse devices are used in the place of the older high frequency generator. Thus an intense ignition spark between the electrode an the surface (distance ca. 3mm) is generated, which pre-ionizes the gas line and allows the arc's ignition.

Application

TIG welding is a commonly used method due to its compact design and the resulting high mobility. Additionally it has a high performance. The TIG method is mainly used in the manufacturing of boilers, tanks, apparatus and tubes and also in the space and aircraft component manufacturing.

Materials

The direct current TIG welding is mainly applied for welding nickel/-alloys, highly alloyed steels, titan, zirconium and tantalum. Alternate current TIG welding is used for aluminium/-alloys, magnesium, brass or berylliumcopper material.

Material Thickness

Generally all material from 0.1mm to several cm can be TIG welded, but the normal material thickness is between 0.5–5mm.

Features

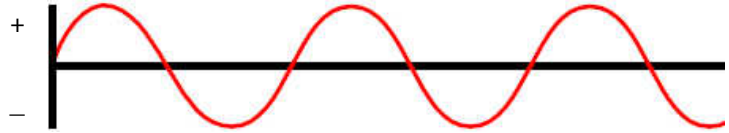
- Welding of Aluminium:

  As known, aluminium builds up an oxide coat. This coat (melting point 2050°C) prevents the floating of the weld pool during welding and therefore the connection of single drops to the weld. For this reason the oxide coat has to be removed from the part's surface by brushing, grinding or bating, if possible, directly before welding.

  The new thin oxide coat, which is regenerated in ca. 5 ms, is during welding with alternate current destroyed in the moment, when the positive pole is located at the electrode (cathodic cleaning, at the same time high heat at the electrode).

  If the negative pole is located at the electrode, a cooling effect does occur. The higher heat at the part's surface is used for melting.

High heat at the electrode + Destruction of the electrode



High heat at the part's surface + Cooling phase at the electrode

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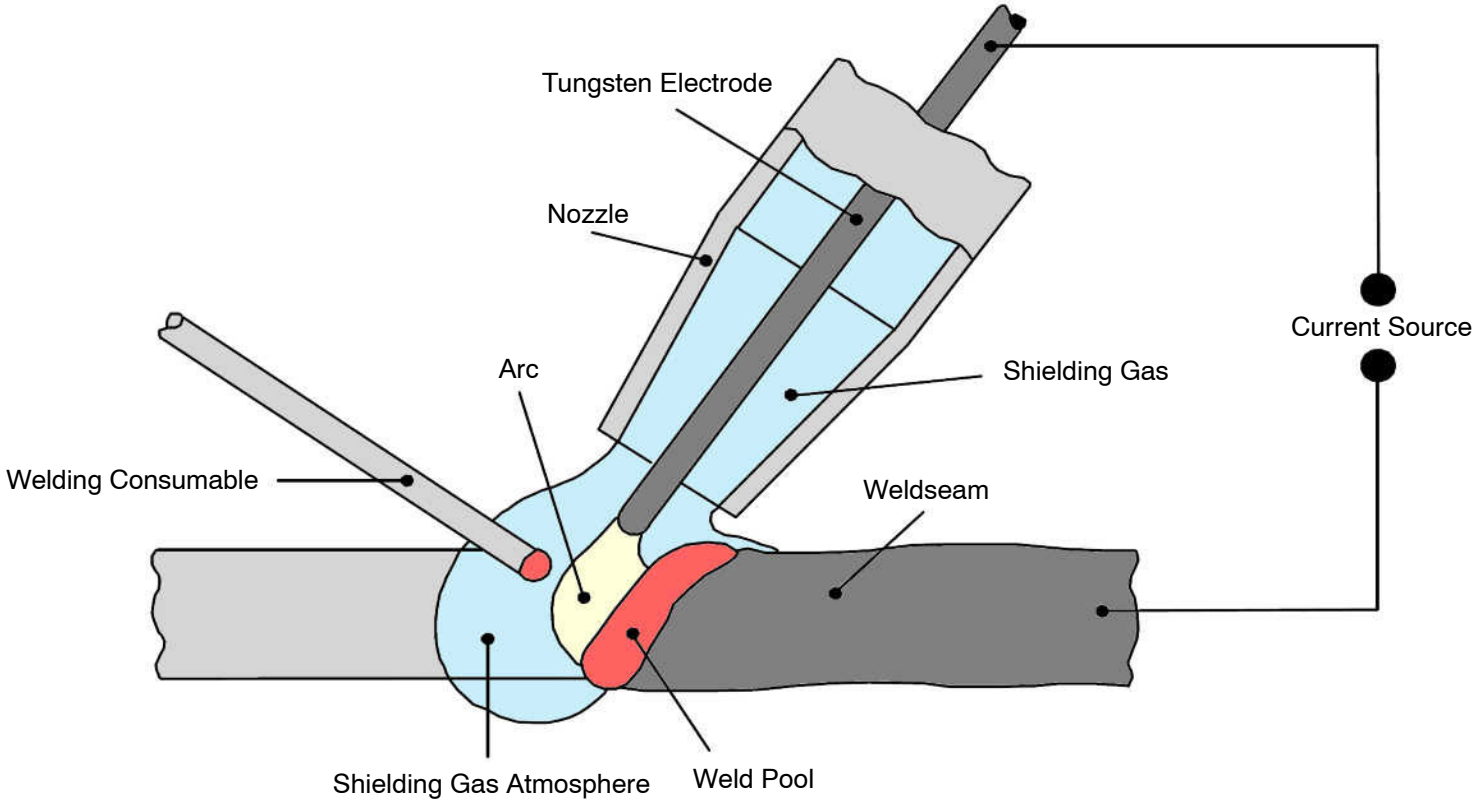


Figure 19 TIG

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PLASMA WELDING

General

Plasma is a gas, which consists out of neutral elements (atoms, molecules), ions and free electrons and which is therefore electrically conducting. It can be produced out of common gases, like e.g. helium or argon, if enough energy is input to them.

Plasma welding means that an arc, which is constricted by a nozzle, is used as a heat source. The cooling effect and the mechanical constriction by the nozzle lead to a considerable reduction of the arc section. The constricted arc is lightening between the tungsten electrode and the part's surface (PAW = Plasma Arc Welding).

The essential point is, that through the constriction of the arc and the plasma gas stream a high energy density is created on the part's surface.

The created weld is very thin and has a smooth surface, whereas the energy input per unit length is lower than during TIG welding und thus the heat zone is reduced.

Application

Plasma welding is used in the chemical apparatus construction e.g. welding of compensators, rubber gaiter or metal sieve. A second application area is the tank construction, here e.g. beer kegs, gas bottles or storage tanks are welded with the help of this method. In the space and aircraft industry this method is used for e.g. the welding of turbine blades.

Materials

The procedure is especially suited for welding austenitic CrNi- and CrNiMo-steels, Nickel, NiCr- and NiCrCu alloys, titan/-alloys, zirconium/-alloys and copper-nickel alloys.

Material Thickness

Depending on the plasma welding procedure material thickness of 0.01mm up to 12mm can be welded with an I-joint. With a Y-joint even thicker materials can be welded, but normally only the root is established with the plasma welding procedure.

Features

- Plasma Jet Welding (PJW)

  Plasma jet welding is done with a negative electrode and a non-transmitted arc. The arc is between the electrode and the nozzle and is heating the plasma gas. The visible plasma gas stream is not electrically conducting, has a lower energy and is used for heating or cutting of electrically non-conducting material and for plasma spray.

- Micro Plasma Welding

  Here special energy sources with 0.05–50A are used. Thus parts in the foil thickness area between 0.01 and 1mm can be welded.

- Key Hole Technique

  In this method the plasma beam goes through the whole part due to a controlled increasing of current and plasma stream. The weld pool is pushed to the sides by the plasma stream. The surface tension prevents a flowing-out of the weld pool until it flows together behind the beam and solidifies to the weld. After that the key hole is closed by reduction of current and plasma stream.

  The advantages of this method are the deep welding effect and the higher welding speed.

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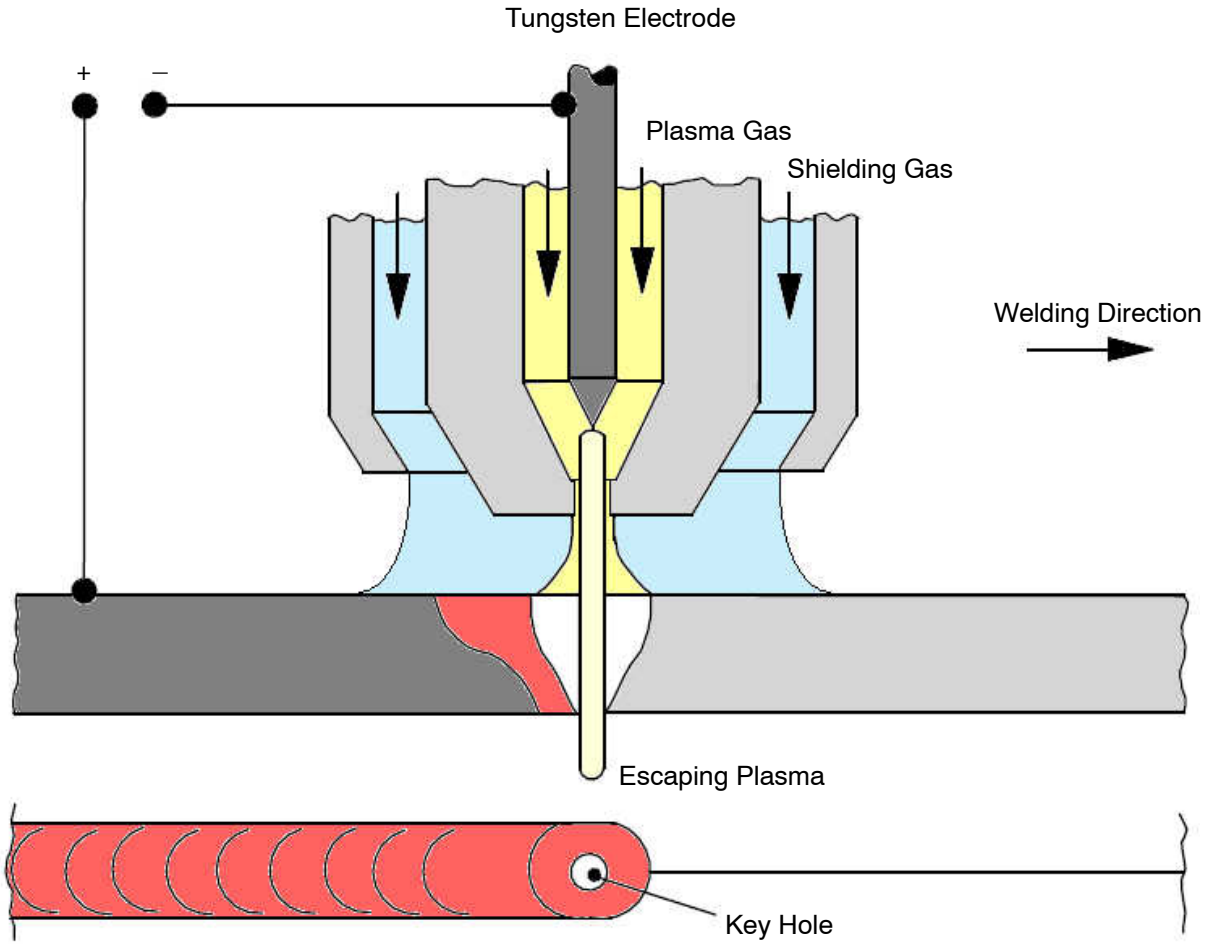


Figure 20 Key Hole Technique

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ELECTRON BEAM WELDING

General

The main principle of electron beam welding is that metals, if they are supplied with enough energy, emit electrons. By focusing and accelerating of e.g. by a tungsten-cathode emitted electrons in vacuum an electron beam is created, whose electrons hit the surface with up to 2/3 of the speed of light (kinetic energy). The released energy (thermal energy) leads to a melting of the material. For welding normally the work piece is moved under a static electron beam. But the beam can also be deflected to sinus, trapezium, saw tooth or circular movements by crossed magnetic coil pairs.

Electron Beam Focussing

The electron beam, which is generated and accelerated by the triode system (cathode, control electrode and anode), is focussed by a DC conducting coil (magnetic focussing lens) and is displayed with high depth of focus and small diameter on the part's surface. The diameter is normally smaller than 1 mm, for precision welding tasks it is between 0.1 and 0.3 mm, for deep welding between ca. 0.1 to 5 mm.

Non-Vacuum Electron Beam Welding (NVEBW)

Electron beam welding is normally done in vacuum, that means not only the generation of the electron beam but also the whole welding process is done in vacuum. For this reason working chambers of up to 1000m^3 for parts and special cases in the space and aircraft industry have been built.

During NV electron beam welding only the generation of the beam is done in vacuum, the welding process is done in the normal atmosphere. In order to minimize the beam's diffusion in the atmosphere and thus create thin welds, the actual welding is done with very small working distances of 6 to 30mm (vacuum: 100–1000mm).

Application Areas

The application areas are due to the very thin but also very deep weld very versatile, e.g.:

- Space and aircraft industry
- Vehicle manufacturing (Gearwheel, pistons ...)
- Tool manufacturing (Steel-carbide-welding ...)

Materials

With the help of this method parts out of non-, low- and highly alloyed steels, copper-nickel alloys, aluminium and tin brass, monel, titan/-alloys, and aluminium/-alloys can be welded.

Material Thickness

With electron beam welding titan alloys with a material thickness of 260mm have been welded. In vacuum a weld-depth/weld-thickness factor of 40:1 is common; when welding under normal atmosphere this factor is reduced to 6:1.

Features

- Electron Beam Drilling

  With this method metals, ceramics and plastics can be drilled. The material is vaporized at the electron beam location via pulse operation. Thus holes with a depth/diameter factor of 80:1 are possible.
- Electron Beam Hardening

  With the help of this method the part is heated locally at the surface up to the austenitic structure. Due to the concentrated, short energy input a self quenching does occur, that means cooling media like water or oil are not needed.

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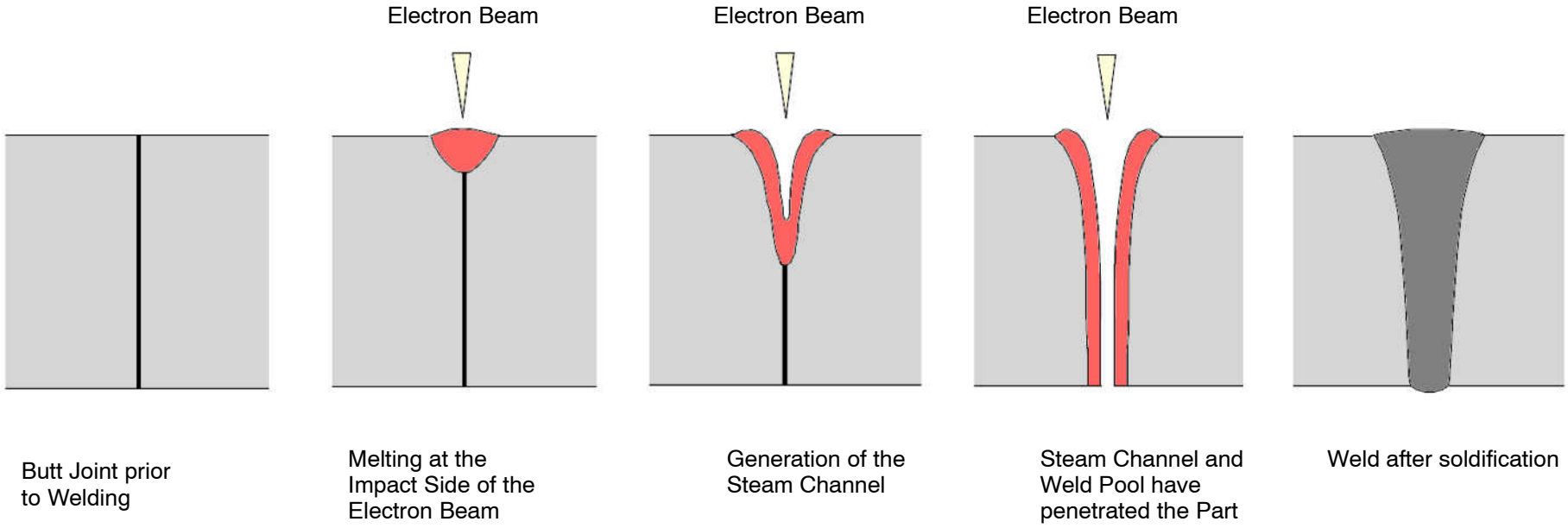


Figure 21 Electron Beam Welding

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LASER BEAM WELDING

Fundaments of Laser Beam Welding

The quantum theory is the fundament for the generation of laser light. The first **Laser** (**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation) was built in 1960 by T. Maiman.

In order to create a continuous laser beam, it is necessary to bring atoms, ions or molecules of an active laser material (Gases, liquids and solid bodies with a meta-stable energy level) in a exactly defined activated state, so that during returning to the nominal or energetically lower state laser light is emitted.

The energy input into the laser allows that the active material is getting into the metastable energy level. This procedure is known as „optical pumping“.

There are different forms of energy input depending on the laser type:

- **Gas Laser** (CO_2 laser) are activated by electron and ion impact.
- **Solid State Laser** are supplied with energy by light.
- **Diode Laser** are electrically operated.
- **Excimer Laser** are activated by high voltage discharge.

Due to stimulated or inducted emission the jump of an activated electron to a lower energy level is stochastical. Since the jumping electron emits its energy, an amplification of the incoming light ray does occur. Thus the fundament of the laser effect is the inducted emission. The complexity in laser design is to generate this inducted emission. This is achieved by pumping as many electrons as possible into this metastable energy level.

Since this level can only be achieved by a detour along a third energy level due to quantum mechanic reasons, lasers always work with three, the most important even with four energy levels.

Nd:YAG - Solid State Laser

In the center of the laser a **Y**ttrium-**A**luminium-**G**ranet crystal, which is doped with ions, is located. Its Y^{3+} ions are replaced by $\mathbf{Nd}^{3+}$ ions. The Nd^{3+} ions are optically activated by bulbs (flash bulbs or arc lamps) and thus are emitting laser rays.

By the usage of a diode laser as a optical pump, it was able to increase the all-over efficiency from $\eta \leqq 5$ % to $\eta \sim 10–12$ %.

Laser Beam Focussing

An interesting aspect is the fact that in industrial production the laser source and the work piece can be arranged separately with a greater or lesser distance to each other. Thus distances from below 1m to 30m are possible. By usage of mirrors, lenses or optical fibres, depending on the laser type, the straight laser beam can be deflected in every wanted direction.

Optical devices focus the laser light to beam intensities of more than 10^6 $W/cm^{2,}$ which are needed for welding.

Application Areas

- **CO_2– and Solid State Laser** are commonly used in the industry for general material machining, like cutting, drilling, stripping or welding. Common areas are e.g. the space and aircraft industry, automobile industry and plant, tank and ship construction.
- **Diode Laser** are applied in e.g. CD/DVD players, laser printers, scanner cash registers, in the telecommunication and in measurement engineering.
- **Excimer Laser** are mainly used in precision- and micro-designs, like e.g. for engraving or for the activation of photochemical processes.

Materials

Generally all materials that can not be welded with conventional welding methods can be welded by a laser beam welding method. Often this method is used for steel and aluminium, but also a mixture of materials, like e.g. the seat rail out of titan and aluminium developed by Airbus, can be machined.

Material Thickness

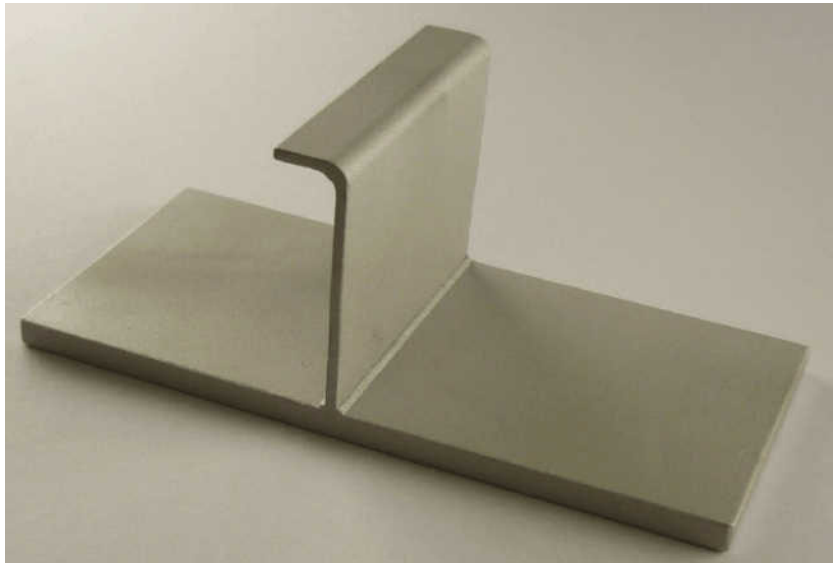
The material thickness that can be machined by laser beam welding in the sheet area are between 1/100mm and 20mm with cutting speeds between 0.1 and 100 m/min.

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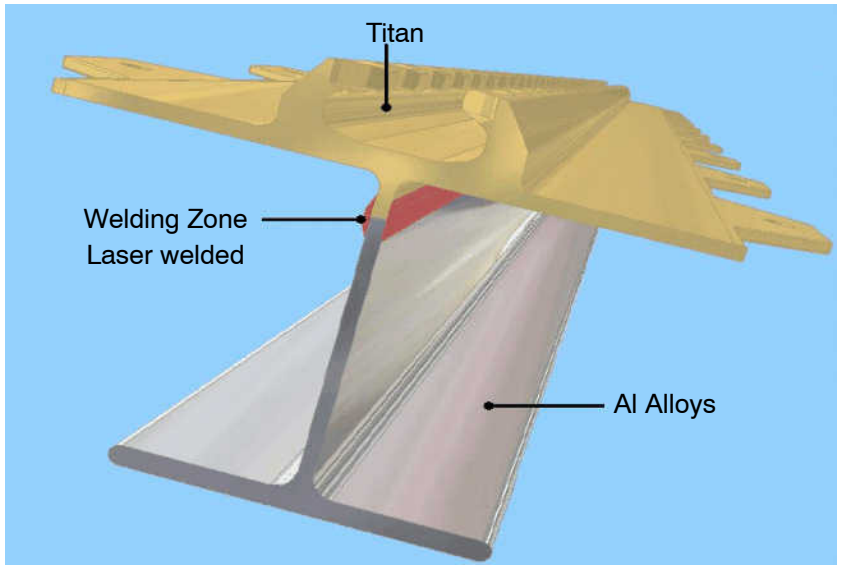


Figure 22 Laser Beam Welding

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Pressure Welding Methods

FRICTION WELDING

General

Friction welding is a quite simple joining process. The thermal energy, which is needed for joining, is produced by mechanical friction (rotation or translation + friction force). When the needed temperature is achieved, the e.g. rotating part is decelerated. By application of a defined upsetting force the two parts are welded. The flare which is generated in the welding zone can be removed from the parts by milling or turning. During friction welding no welding consumables are needed. Also a shielding gas is not necessary (Machining of the weld).

Rotational Friction Welding

The heat, which is needed for the joining process, is applied by a rotation (rotational movement, generated directly or by an inertia drive) and a friction force. This method is e.g. suitable for the joining of tubes or shafts.

Linear Friction Welding

The heat, which is needed for the joining process, is applied by a translation (linear movement) and a friction force. This method is e.g. used for manufacturing of blisks (bladed disks = integral rotors, compressor/MTU).

Materials

An important advantage of friction welding is the fact that no only identical materials can be joined but also material combinations, like e.g.:

- Ferritic with austenitic steel
- Aluminium with steel
- Steel with copper
- Aluminium with copper
- TiAl4V with columbium (Cherry-Buck Rivet)

Material Thickness

Today friction welding is used for joining diameters between ca. 7 and 200 mm (tubes up to 400 mm).

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Linear-Friction-Welding of a so called „Blisk“ (MTU)

Figure 23 Friction Welding

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FRICTION STIR WELDING

General

Friction stir welding (FSW) is a subtype of friction welding. The characteristic of this method is that parts made out of the same or different materials are joined in a butt or lap joint.

In this method the process heat and pressure are generated by a cylindrical tool, at whose end the so called molded welding stud is located. The tool is moved, while it is rotating, on to the joint location until the shoulder of the tool touches the surface. The heat generated by the friction makes the material soft.

If the necessary process heat is achieved, the linear movement, which start at this phase, results in a stir of the material and leads it to the backside of the tool. Due to the pressure applied at the same time, the material is compressed and solidifies during cooling.

The process characteristics, which have to be chosen in accordance to the material, are rotating speed, axial pressure and welding feed.

Application

This method is used in many industries. In the automobile industry, e.g. for the Audi (R8), transmission tunnel closing plates are manufactured with this method out of materials with different thickness (1.7 + 2.4mm).

In the aircraft industry e.g. the skin panels of the Airbus A380 airfoils are welded with this method.

Materials

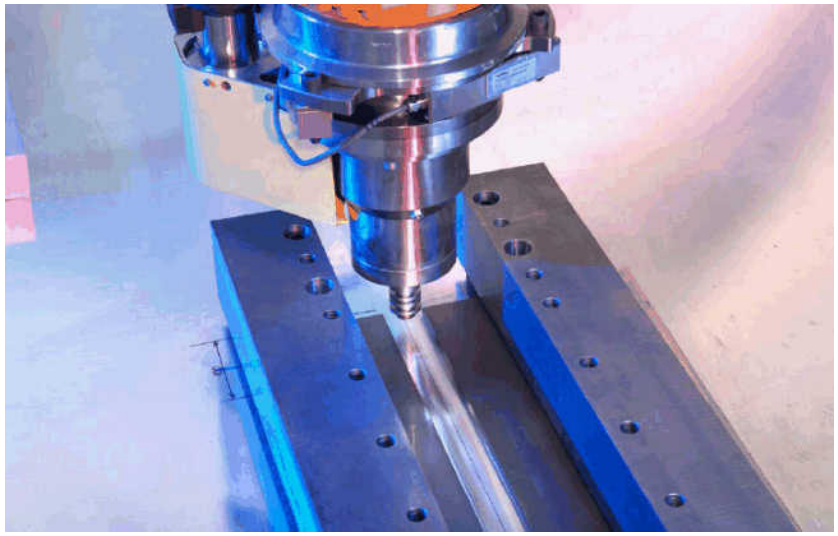
Mainly light alloys like aluminium/-alloys, but also combinations like e.g. aluminium - stainless-steel are joined together.

Material Thickness

In material thickness that can be treated with FSW are between 0.5 - 20mm in one work sequence with a feed of up to 4 m/min.

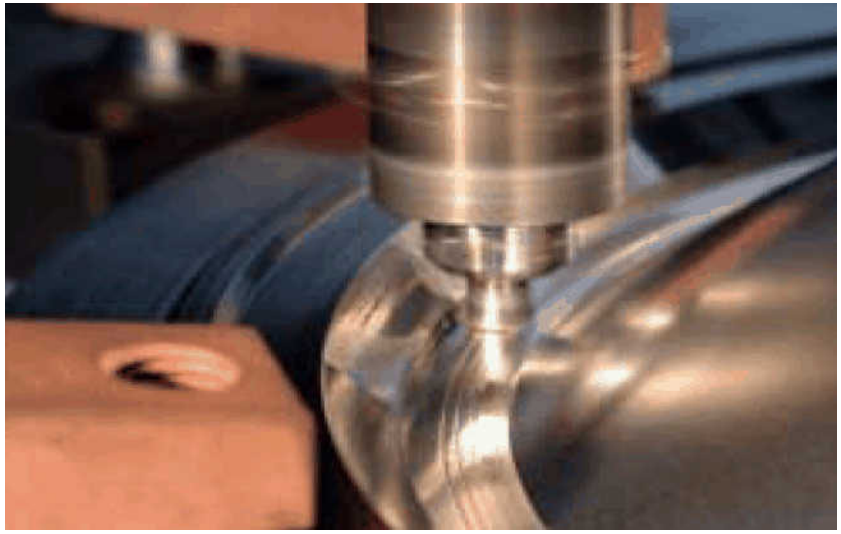
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Tank Turret of the second Stage of Ares I (NASA)



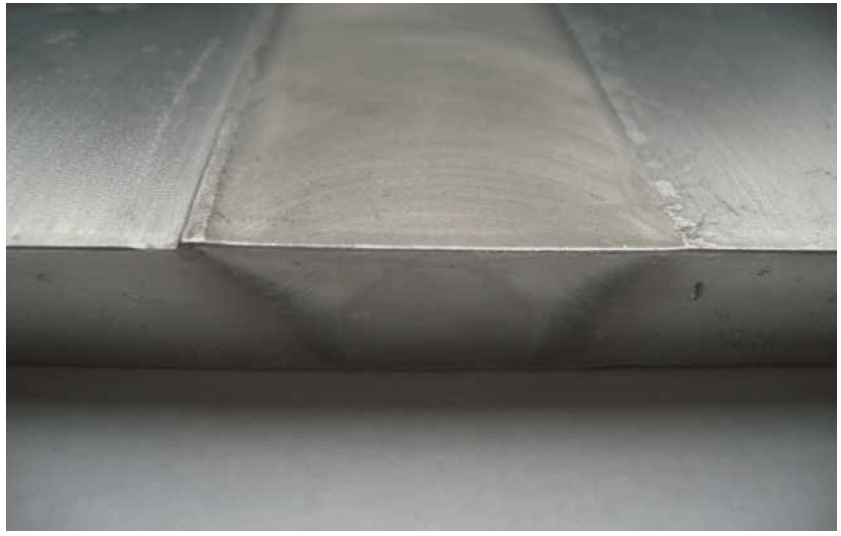


Figure 24 Friction Stir Welding

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DIFFUSION WELDING

General

The main principle, on which diffusion welding is based, is the transposition in solid materials, that means the generation of a joint through diffusion processes between both of the materials that have to be joined.

The connection between the mating surfaces is done under pressure and heat.

In this welding method no weld pool and just a very small macroscopic deformation during the joining process does occur.

In the ideal case a diffusion weld between the same materials can not be identifies and has the same characteristics as the basic material.

Diffusion welding can be done with or without a filler material, which e.g. can be used as a diffusion aid for the joining of different materials.

Complex parts out of materials that can hardly be joined can be manufactured cost efficiently via diffusion welding.

This method is especially suitable for materials or geometries which can not be welded with conventional methods.

Application

This method is widely used in aircraft and space industry, medical technology and in micro-, laser- and optical-systems technology.

Materials

With each other and among each other the following materials can be joined:

- Light alloys (Al, Ti, Mg)
- CRES
- Sintered hard metals

and non-metallic materials, like:

- Glass
- Plastics
- Crystals
- Ceramics

Material Thickness

The material thickness is not important and is only limited by the machine size

Advantages and Disadvantages

Advantages are:

- Cost efficient method for complex parts like: Tools, gear parts, cooler
- No negative characteristics of the welding zone
- Connection between different materials possible
- can be applied, where conventional welding methods are not successful

Disadvantages are:

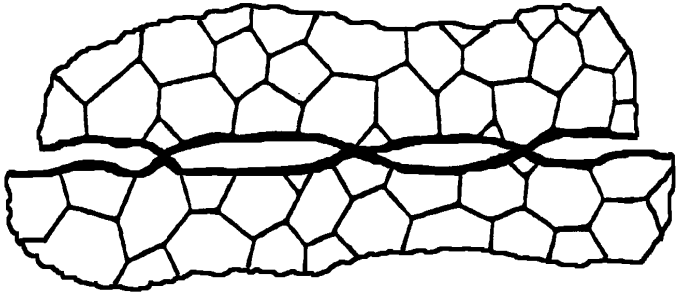
- High machine effort
- Long process time
- High requirements to the surrounding atmosphere
- High requirements to the joining surfaces (surface pollution must be destroyed or distributed in such a fine way that the metallic connection between the parts can start)

Sequence of the Diffusion Welding Process

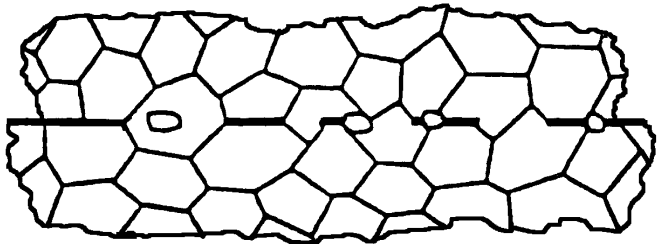
For a conventional diffusion welding process without a filler a three stage model describes the development of the joining process between two parts.

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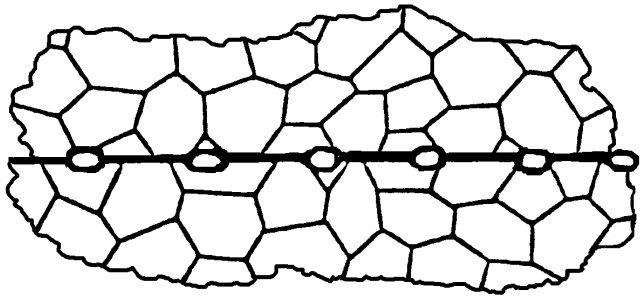
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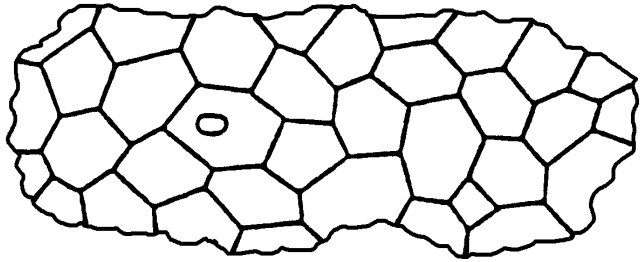
Initial, sporadic Surface Contact



In the 2. phase the diffusion gets more important than the deformation. Many pores vanish since the grain boundary diffusion of the atoms still lasts. At the same time the grain boundaries at the contact surface wander out of their layer until a certain balances state is achieved. Some pores remain now in the grain of the structure.



In the 1. phase the deformation of the surface irregularities does occur caused by strain and creep. Thus large contact surfaces arise. After the 1. phase the connection is mainly made out of grain boundaries at the contact surfaces.



In the 3. phase the pores vanishes caused by mass diffusion. In the process lattice variances wander from the pores to the structure.

Figure 25 Joining Process during Diffusion Welding

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SUPERPLASTIC FORMING

General

The technology of superplastic forming uses the very high flowability of metallic material at high temperatures.

The characteristic achieves titan e.g. at ca. 900°C, which can be attained by heating in a hot press.

By blowing in the inert gas argon under relatively low pressure (up to 10 bar for titan) and, if needed, vacuum at the forming side, the material gets the form of the forming tool. Thus very thin but nevertheless dimensionally stable geometries are realizable.

This method makes it possible to produce complex surface structures with exactly predetermined wall thickness. Due to the high deformation, for titan 1500%, also complex parts are possible.

Superplastic forming is due to its low tool costs and the small material effort especially economically suitable for series production

Materials

Mainly light metals like aluminium/-alloys alloys, titan/-alloys and magnesium/-alloys are suitable for this method, but also steel and nickel/-alloys, like Inconell 718, can be treated with superplastic forming.

Material Thickness

The material thickness are between 0.1 and 22mm.

Advantages and Disadvantages

Advantages are:

- Cost reduction through series production
- Weight reduction
- Complex geometries realizable

Disadvantages are:

- High machine effort
- High energetic effort

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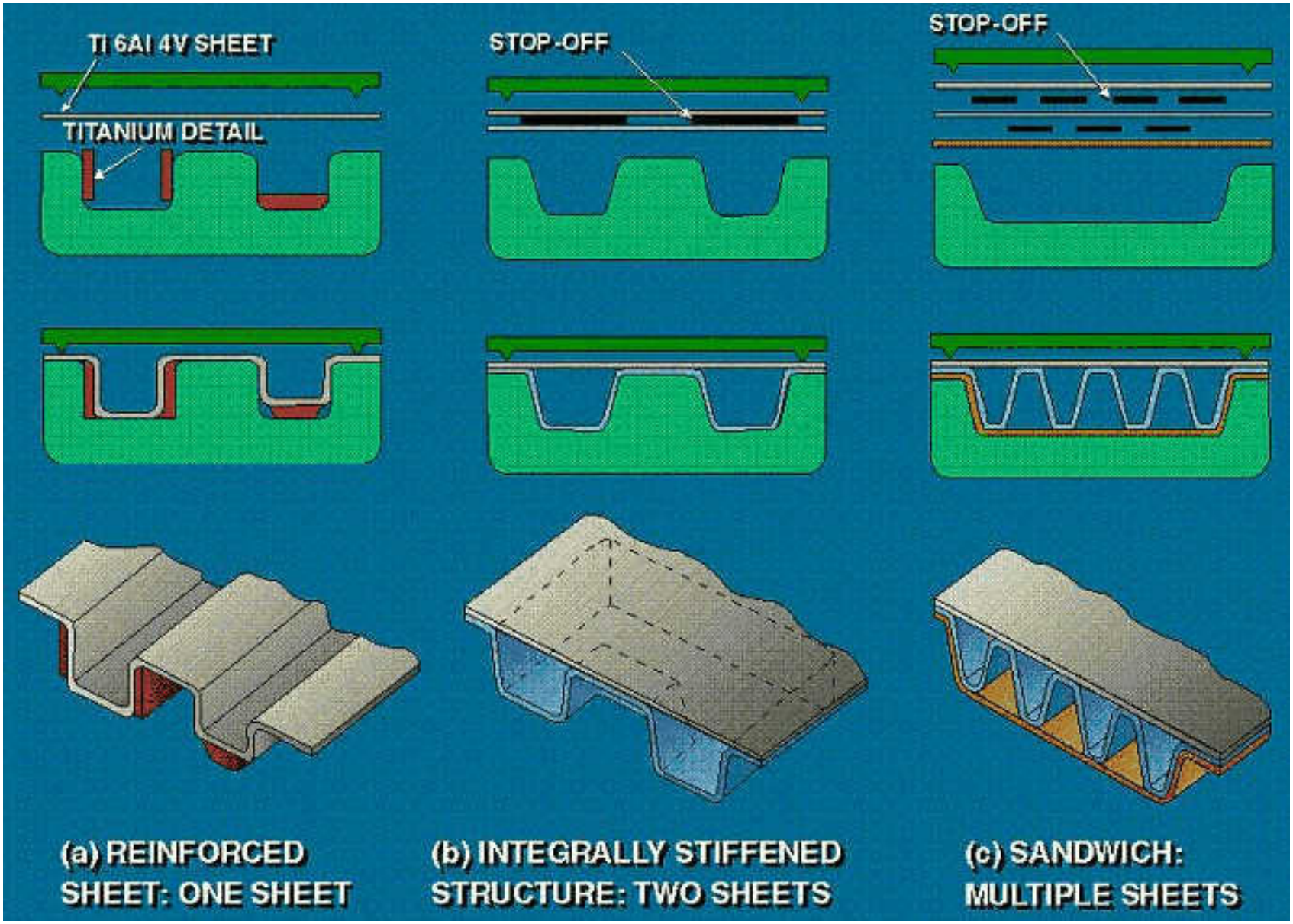


Figure 26 Superplastic Forming Process

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Application Examples for superplastic Forming

This method is used in many industry types, like e.g. automobile industry (Aston Martin Vanquish: bonnet, front fender, rear part out of Al; Morgan: front and rear fender out of Al).

In the space and aircraft industry among other things the fuselage end caps of Airbus planes, the wing tips of Boeing 777, pylon leading edge skins of Boeing 737, cargo door inner skin of Learjet 45, landing light housing of A340, engine- and bleed air ducts, fan blades of RR engines for B 787 and A380 up to the planking panels of the ISS are manufactured with the help of this method.

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Boeing 777 Wing Tip Aluminium Alloy, Thickness: 3mm



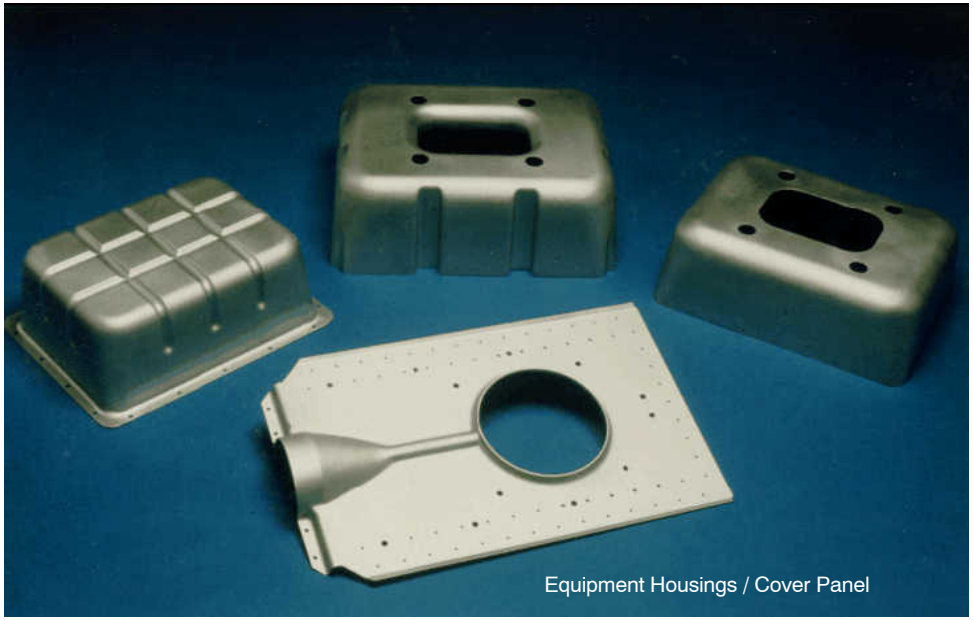
Boeing 737 Pylon Fairing



Boeing 737 Pylon Fairing



Rolls Royce Fan Blade



Equipment Housings / Cover Panel



Airbus A340–5/600 Landing Light Housing

Figure 27 Examples of SPF-Parts

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Combination of Superplastic Forming and Diffusion Welding

In order to manufacture complex parts, especially hollow structures, both methods superplastic forming and diffusion welding can excellently be combined.

For this firstly the parts are clamped in a forming press and then are formed in a heated state

After the forming process the forming tool temperature is slightly increased. Afterwards the mold halves are pressed together. by this the contact surfaces of the parts are joined by diffusion welding.

By the combination of these two methods even the manufacturing of hollow structures with integral reinforcements are possible, for whose production no other method is available.

Application

In the aircraft industry e.g. Manhole Covers of some Airbus aircraft types and slat cans are produced with this method.

Materials

This combination of SPF and DW is mainly suitable for titan/-alloys and aluminium/-alloys.

Advantages and Disadvantages

Advantages are:

- Weight reduction
- Realization of complex forms, even hollow bodies with integral reinforcements
- No other method is available for the production of parts described above

Disadvantages are:

- High machine effort
- High energy effort

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Figure 28 Airbus Manhole Cover in SPF and Diffusion Welding Technique

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BONDING METHODS AND INSPECTION OF BONDED JOINTS

Bonded Joints

BONDING GENERAL

Definition „Bonding“

Bonding describes mostly non-detachable joints between the same or different materials.

Bonding Procedure

The connection of these materials is done with the help of a adhesive, which is brought between or on the materials. A bonded joint is thus a firmly and permanent surface joint by a adhesive layer.

Bonded joints are classified as substance-to-substance joints, since molecular forces of the adhesive are present between the parts that have to be connected.

Strength of the Adhesive

Both internal strength (cohesion) and the possible contact force (adhesion) of the adhesive have high influence on the strength of the joint. In an adhesive-friendly designed joint these two forces have always to be higher than the outer load.

Thus an adhesive has to withstand the separation of the connected parts by the formation of adhesion and cohesion forces.

Bonded Joints General

Bonded joints are, due to their characteristic advantages and disadvantages, a competing but also a complement method to other joining methods.

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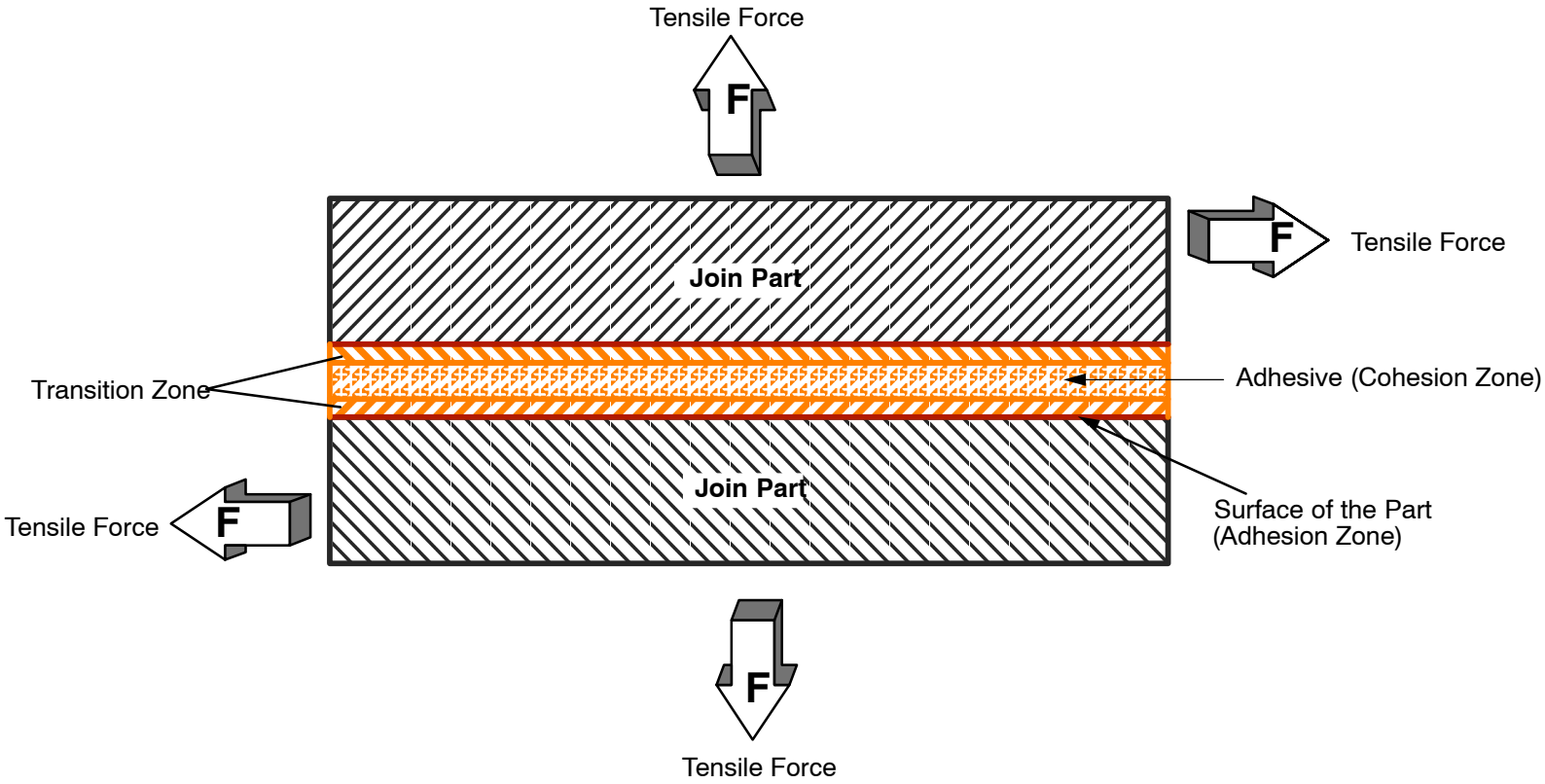


Figure 29 Bonded Joints General

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PRINCIPLE OF ADHESION ACTION

Adhesion of two Join Parts without the Influence of Air

Atmospheric air pressure presses two smooth surfaces with parallel faces together, provided there is no air between the contact surfaces.

Cold Weld

In outer space, “cold welding“ would be the result. Even in our environment, especially high-grade surfaces like on-end measures or master gauges tend to “cold weld“.

Experiment

Experiments have shown that you can bond two glass panes with parallel surfaces with Vaseline to such a degree that you cannot separate them manually with a force acting in a vertical direction to the surfaces.

The reason for this is simply our normal barometric air pressure, which at sea level amounts to 1 bar or 10 N/cm^2.

A relatively small contact area of 100 cm^2 needs a perpendicular pulling force of 1000N to separate the glass panes from each other.

Vaseline is a viscous contact that prevents air pressure entering between the panels, but a lateral movement of the panels in relation to each other cannot be prevented.

The experiment can also be carried out with fluids of a lower viscosity such as water, but then the panels can be separated quite easily.

If the Vaseline is replaced with an adhesive, a mechanical application of load to the bonded parts becomes possible.

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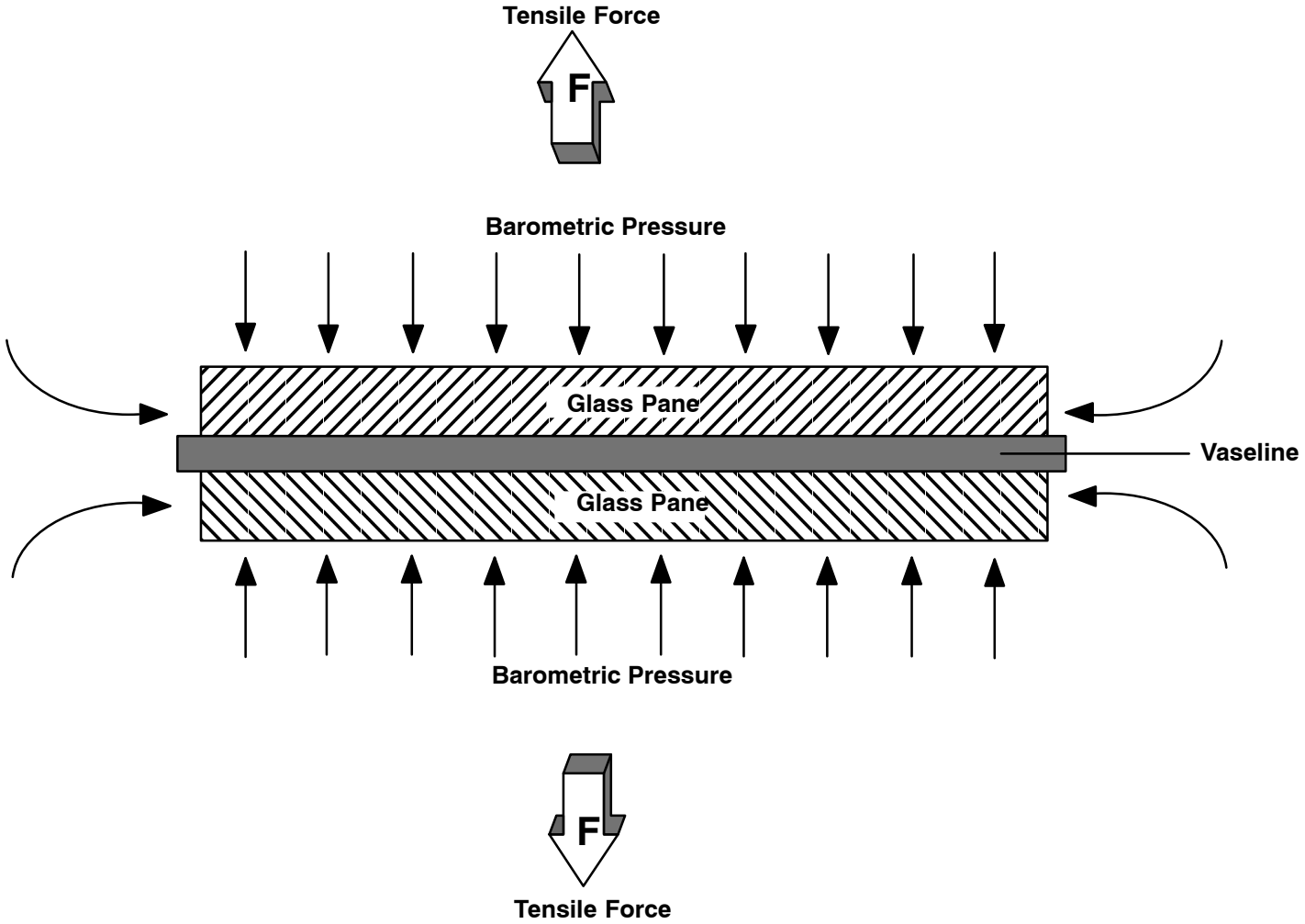


Figure 30 Principles of Adhesive Action

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Wetting

General

An important condition for best possible bonding is the ability of the adhesive to cover the complete surface of the parts to be joined, and to ensure a good contact (wetting capability).

Bad Wetting

Mercury, for example, is a fluid which does not wet most metallic and ceramic materials. The flattening of the mercury drop is caused by gravity. The mercury drop forms into a ball due to strong internal cohesion forces of the atoms, which attract each other.

Good Wetting

In contrast to mercury, a fluid that will provide good contact with the surface will make it wet.

A so-called penetrating oil will even cover the complete surface of a part that is facing the ground.

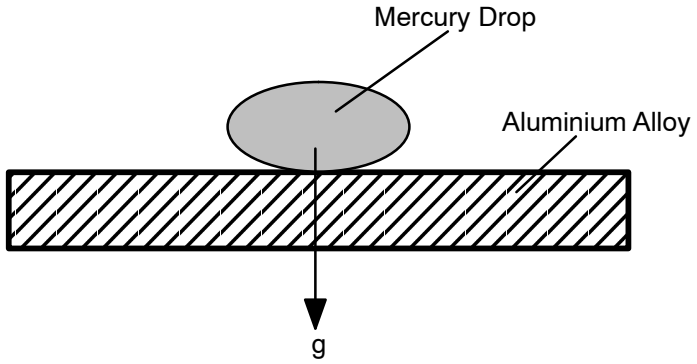
Epoxy-resins used in airplane manufacture get in good contact with the surfaces of the parts if they have been pretreated correctly. However, not every material surface will have a good contact with epoxy-resin. The automatic covering of Teflon, for instance, is not possible.

The contact of the fluid and the surface occurs because there is a mutual attraction between the fluid and the surface. This can be stronger than gravity. The fluid can „creep“ along the surface.

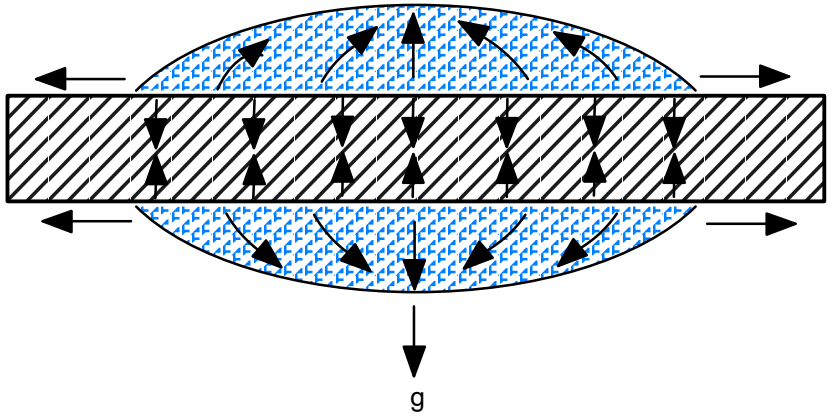
Only if gravity is higher than the contacting force will the fluid drop from a surface that is upside down.

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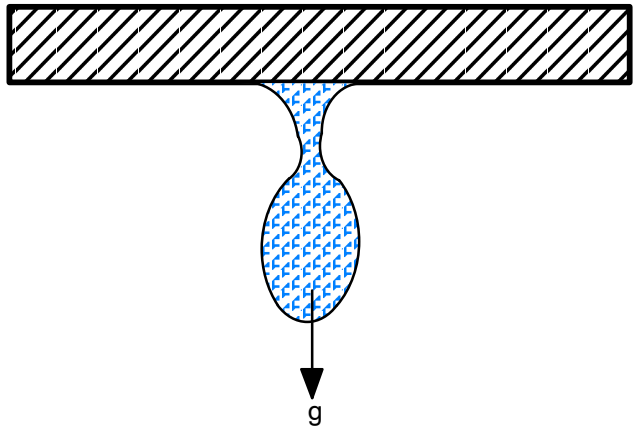
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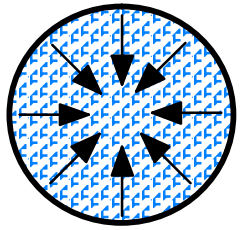
Bad Wetting of Mercury on Metal



Good Wetting of a Fluid, both on the upside as on the downside of the part the fluid is creeping automatically since the Adhesion Force is stronger than the Gravity



Bad Wetting since the Gravity is stronger than the aadhesion Force of the Fluid



Since there is no Gravity in space the Fluid would form automatically a sphere

Figure 31 Wetting

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ASSESSMENT CRITERION FOR WETTING

General

In order to classify the wetting ability of different substances, exact definitions must be found.

Here the so called wetting angle of the substance is essential, which can be measured after application of the substance on to the surface of the join part.

It is now looked at the wetting angle which is the opening angle between the part's surface and the applied substance.

Assessment Criterion for bad Wetting

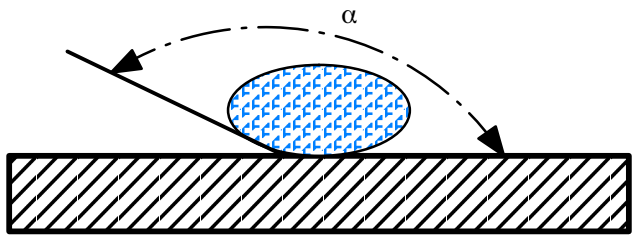
Substances are classified as substances with bad or no wetting ability, if the wetting angle of the substance on the surface has an opening angle of less than 90°.

Assessment Criterion for good Wetting

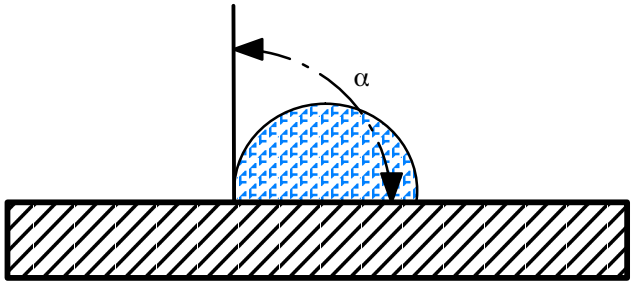
Substances are classified as substances with good wetting ability, if the wetting angle of the substance on the surface has an opening angle of more than 90°.

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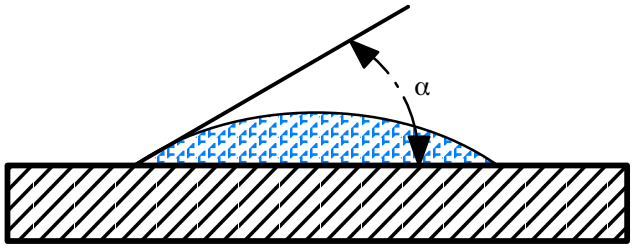
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α = Wetting Angle



α ≧ 90° = No Wetting



α ≦ 90° = Good Wetting

Figure 32 Assessment Criterion for Wetting

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Capillary Action

General

If conditions for a good contact are right, the narrowness of tubes and gaps in adjacent material will add to it. Fluid will enter the narrower the cavity is.

Here it is valid: The narrower the gap, the better the wetting. This effect is called capillary action.

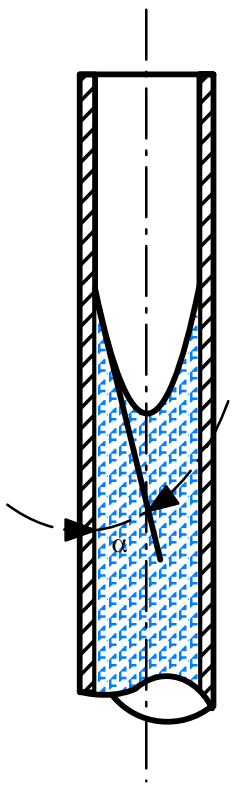
The same effect is used in soldering (relation between soldering and bonding).

The following descriptions refer to capillary action in narrow tubes or gaps, for example in sheet metal panels in contact with each other.

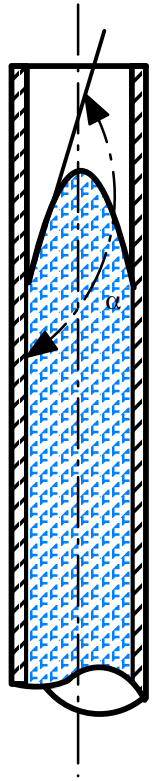
It is clear that in the cabin interior area (such as in the galley and lavatory areas) a lot of corrosion damage is caused because aggressive fluids penetrate between borders of floor panels or under supported masking panels. The wetting forces are usually so strong, that an evaporation of the penetrating fluid does not take place.

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Good wetting - good capillary action



No wetting - no capillary action

Figure 33 Capillary Action

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Adhesion and Cohesion

General

The Quality of a bonding depends on the factors adhesion and cohesion.

Adhesion

Adhesion (lat. adhaerere = „to stick“, also known as adherence) describes the attractive force between adhesive molecules and a part’s surface.

These attractive forces are based on the molecular interactions between different materials, whereas the adhesion energy, the adhesion work of the material, is a criterion for the strength of a bonded joint.

Examples for adhesion are:

- Chalk on a board,
- Printer’s ink on paper,
- Epoxy resin on metal surfaces.

This adhesion will only be effective if the surfaces of the parts has been cleaned and degreased carefully.

Should it be necessary, the surface can be enlarged by roughening or an etching bath (pickling). Hereby the adhesive’s mechanical adhesion to the pores and pits of the surface is increased.

Cohesion

Cohesion (lat. cohaerere = „to be connected“) describes the bonding force between atoms and molecules of materials.

So for adhesives cohesion describes the forces, which define the coherence of an adhesive.

The cohesion affects the on the one hand the viscosity (ductility) and the flowability of the adhesive during production phase and on the other hand the strength of the cured adhesive (breaking load)

Cohesion is always known. The breaking load of an adhesive is determined by tests carried out by the manufacturer. The adhesive is provided with a certain minimum breaking load so that the airplane manufacturer can rely on a fixed bonding strength.

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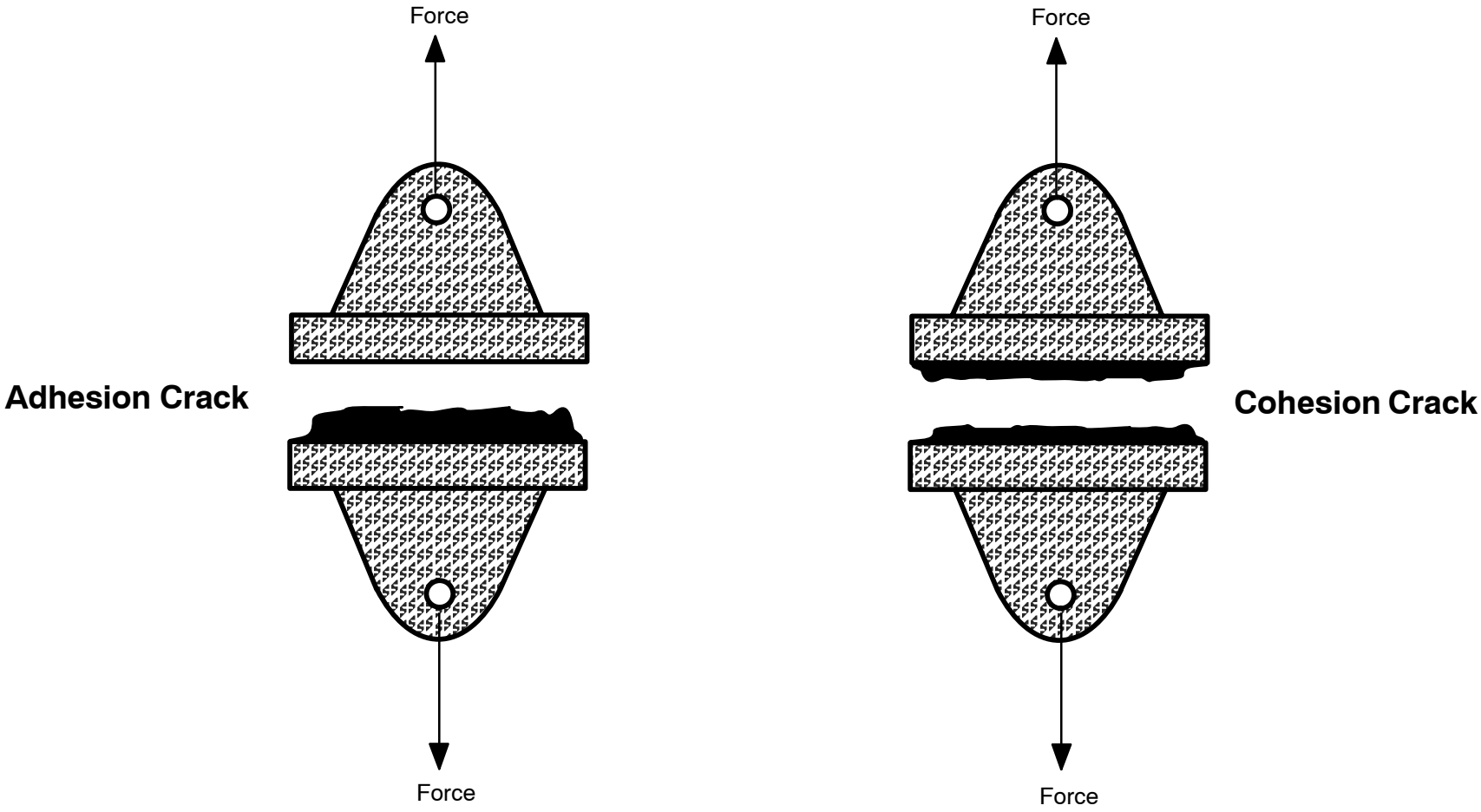


Figure 34 Adhesion und Cohesion

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Adhesives

General

Adhesives are defined as non-metallic, plastic, liquid or solid materials, which can join parts by cohesion and adhesion. The characteristics and the structure of the join parts are not changed.

Classification of Adhesives

In this document different adhesives are classified according to their solidification mechanism that means how they adhere.

A classification can also be done according to a chemical basis (thermoset, elastomer, etc.), but is not reasonable, since there are adhesives, which cure as a thermoset, elastomer or a thermoplastic.

Physical Setting

Physical setting adhesives means that the final adhesive, the polymer by itself, is brought onto the bonding surface.

Here a physical procedure is used, which transforms the adhesive into a processable form, in order to let it solidify and cure in the bonded joint.

Chemical Setting

In chemically setting adhesives, so called reaction resin adhesives, the single chemical parts of the adhesive are brought onto the bonding surface in the right mixing ratio. The setting, curing, occurs due to the chemical reaction between these parts.

Generally reaction resins are classified into the subgroups one- two and multi-component adhesives.

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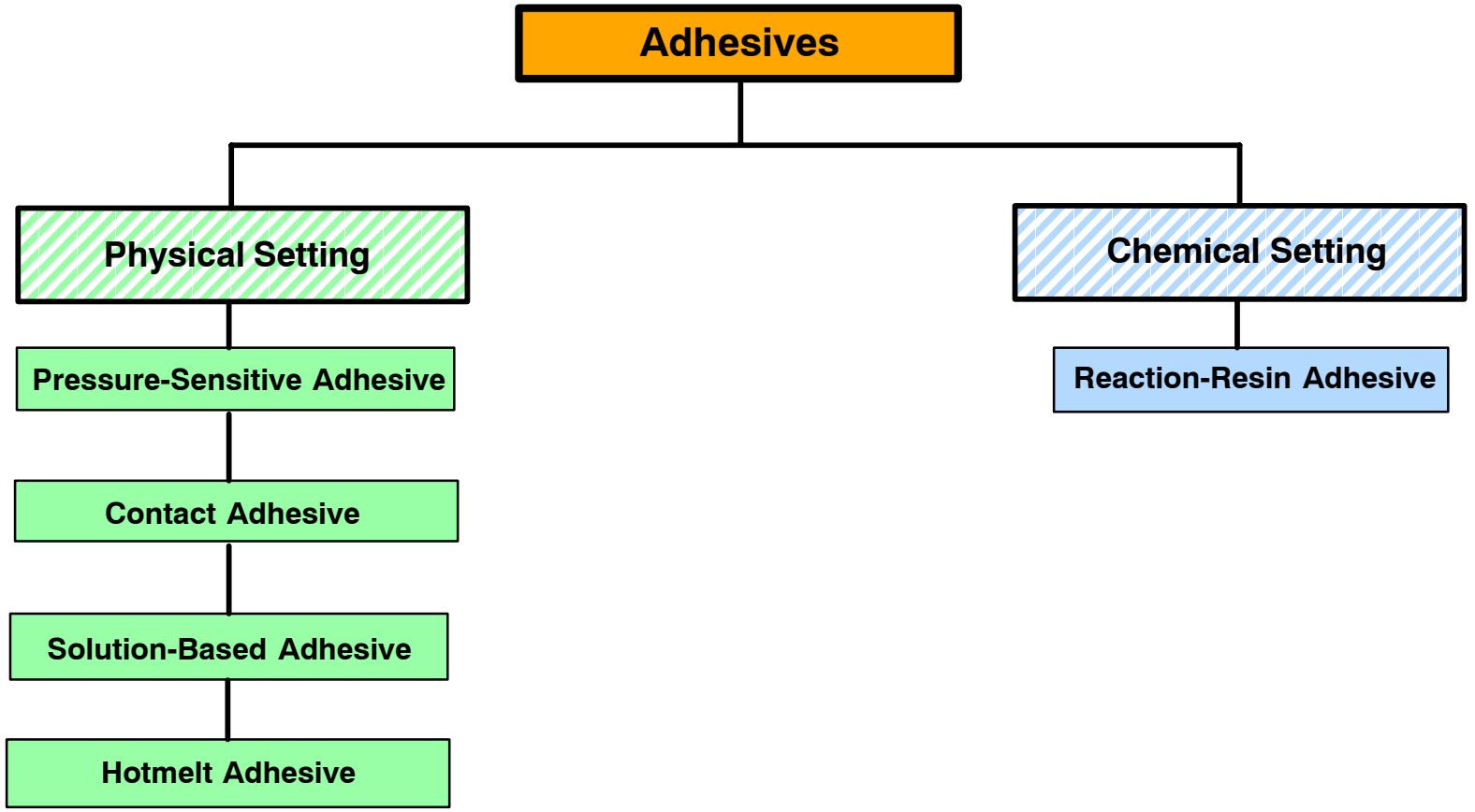


Figure 35 Classification of Adhesives

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Types of Adhesives

PRESSURE-SENSITIVE ADHESIVE

Pressure-Sensitive adhesives are elastically permanent sticking self-adhesives often with high adhesion and low cohesion forces.

These self-adhesives already stick very well under weak contact pressure and room temperature on several surfaces. This bonding can, if applicable, be dissolved several times.

Pressure-sensitive adhesives are tuned to a special form of application since they do not technically cure after application.

Application

Pressure-Sensitive Adhesives are used as:

- Transfer Adhesive (carrier-free, double sided adhesive tape on waxed transfer paper)
- Coating of adhesive tapes and self-adhesive labels
- Adhesive stripes on residue-free adhesive labels
- Coating of sticking-plaster
- etc.

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Figure 36 Examples for Pressure-Sensitive Adhesives

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CONTACT ADHESIVES

Contact adhesives can be solution-based adhesives and dispersion adhesives (e.g. Ponal-Wood Glue), which are handled with the contact adhesive procedure.

Polymers, which merge after evaporation of the solvent/water from the amorphous to the crystalline state and thereby increase their strength significantly, are used as binders for this adhesive type.

Contact adhesive are evenly applied on both sides of the joint. After the necessary airing time (mostly 5 to 15 minutes) is over and the adhesive has a dry surface, both sides are exactly joined together with a preferably high pressure. After joining a correction is not possible.

A determining factor for the joint's strength is the size of the pressure applied, not the length of the pressure time.

Adhesive bonding with contact adhesives are directly after compression able to work and if applicable stay even elastic.

The final strength of the joint is achieved after several days since residue solvent/water are evaporated from the joint.

Application

Contact Adhesives are e.g. used in:

- Textile floor coverings in the cabin interior
- NTF coverings (Non Textile Floor) in entrance, galley and lavatory area.
- Shear protection stripes (e.g. as a trolley protection in galleys)
- Sound insulation material on e.g. ceiling panels
- etc.

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Figure 37 Examples Contact Adhesives

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SOLUTION-BASED ADHESIVES

In solution-based wet adhesives the polymeric adhesive is present in a solved form and is applied in this form on one side of the bonding.

The joining of the two parts is done at a time, where there is still enough solvent in the adhesive mixture, in order to assure the wetting of the second join part's surface.

The adhesive is then hardening by evaporation of the solvent. At this the adhesive is getting more ductile and hardens continuously until reaching the final strength.

Solvent-Based Adhesive as Diffusion Adhesives

Solution-based adhesives can also be used for diffusion bonding (cold welding) of thermoplastics. Both surfaces are treated with the adhesive. The solvent in the adhesive then starts to solve the surface of the join parts. After a short time both parts are pressed together with a certain pressure.

During joining the freed polymer chains of the two treated surfaces interpenetrate. After the escape of the solvent an adhesive bonding is generated, which is based only on cohesion forces.

Solution-based adhesives can also be used to make rubber products soft (e.g. the tube of the tire of a vehicle and the respective patch).

Generally, the usually paste-like solutions can only be used for certain materials. For example, it is not possible to use a polystyrene adhesive to bond a rubber patch or to combine polyurethane parts with a PVC adhesive.

Application

Solution-based adhesives are used in:

- The bonding of NTF layers (Non Textile Floor) in entrance, galley or lavatory areas
- The bonding of PVC tube joints in the cabin interior area (e.g. as cable conduits in/behind partition walls or linings
- And in numerous non-aircraft applications

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Figure 38 Examples Solution-Based Adhesives

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HOTMELTS

Hotmelts are thermoplastic adhesives. They are solid at room temperature; by heating them with special tools the adhesive is melting and they can be processed.

The application of the up to ca. 200°C hot fluid adhesive is done on only one side of the joint. The parts are assembled and directly after the adhesive's cooling and solidification the final strength of the bonding is practically achieved.

In a production process this bonding methods allows very short cycle times and a direct further processing of the joint parts.

In comparison to hotmelt guns and hotmelt sticks used in the in the DIY area, in industrial applications films, pellets and blocks are used, which are processed with melting devices and application heads.

The Usage of hotmelts is, due to their high processing temperatures, limited to temperature resistant materials.

An advantage is that the adhesive has a reversible characteristic, that means under high temperatures the adhesive is getting soft and the bonding can be solved.

Application

Hotmelts are used in:

- Decorative foils in the cabin interior area
- The packaging industry
- The DIY area
- etc.

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Figure 39 Examples Hotmelts

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REACTION RESIN ADHESIVES

General

Due to high demands, like e.g. strength, better creeping, chemical stability and heat resistance, the normal construction adhesives are thermosets.

Here the cross-linking process after application can vary, depending of the adhesive used, and can be generated by a polymerization, polyaddition and polycondensation.

For construction often used basic adhesives form the group of reaction-resin adhesives are:

- Epoxy resin adhesives
- Phenolic resin adhesives
- Acrylic resin adhesives
- Polyurethane adhesives

To enhance the characteristics or to adjust the adhesive to the environment these basic adhesives are often modified with other polymers (e.g. elastomers).

One-Component Reaction Resin Adhesive

Although thus all reaction-resin adhesives have to be made out of a minimum of two components, you speak about one-component reaction resin adhesives, if the components are already mixed by the manufacturer in the supplied to customer condition.

In one-component reaction resin adhesives the hardening or curing process is not activated until special reaction conditions occur, like high temperatures (heat curing), UV irradiation, humidity, exclusion of air, exposure to oxygen or also contact to metal.

Two-Component Reaction Resin Adhesive

A reaction resin adhesive is only denominated as two-component reaction resin adhesive, if the particular components are mixed directly before the application.

Two-component reaction resin adhesives can thus cure at room temperature. The second component is generally an accelerator substance and is therefore also called hardener.

Here the exact dosing, the right mixture, of the components has to be regarded.

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Figure 40 Reaction Resin Adhesives

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Preparation of an Adhesive Bond

General

To get the best bonding connections, several conditions have to be satisfied:

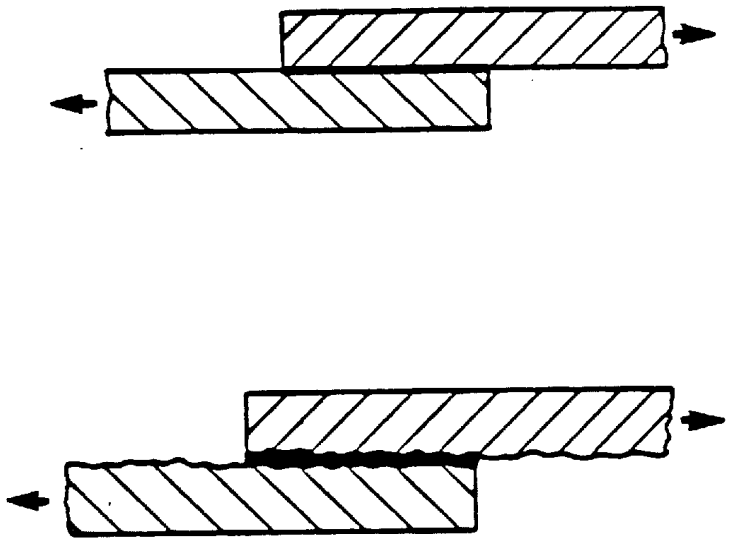
- The interfacial surface forces between the surfaces of the joined parts are enlarged by a submicroscopic treatment (pickling bath, chromic acid anodizing).
- A slightly-roughened surface offers a better contact between the parts to be joined and the adhesive.
- The „real“ surface is slightly enlarged and this makes the bond tighter.
- Mechanical roughening as is sufficient for most bonding connections is not permitted for high grade connection by means of adhesive films and curing in an autoclave.
- The pretreating of adhesion surface areas of sheet metal parts out of aluminium or aluminium alloys is performed on the basis of chemical etching.
- The pickling process is modified by some airplane manufacturers. There may be differences between Airbus and Boeing.
- The result of the pickling or CAA process is a sheet-metal surface covered with micro-depressions.

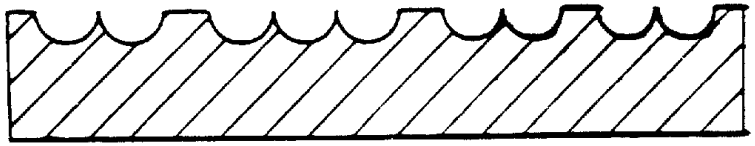
Adhesive can only reach its full stability when being correctly processed:

- Only use new adhesives and not those whose usability has expired.
- Mix adhesives consisting of different components in the correct ratio and process at specified temperature and humidity.
- Observe pot-life time under all circumstances.
- During hardening time, the parts must not be in contact with each other.
- Ensure the correct temperature and sufficient time for the hardening and curing procedure.

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The micro-depressions should be 6 to 7 μm in diameter, the depth 2 to 4 μm.

Figure 41 Effect of Surface Roughening

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Failure Modes of Adhesive Bonds

Influence of Adhesion

The following rule will ensure that you can utilize the full bonding strength of the adhesive and still prevent breakage of the bond during operation of the aircraft to a very high degree:

ATTENTION: Adhesion must be stronger than cohesion!

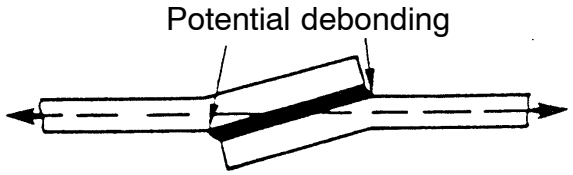
This means that the surface always must be pretreated in a way that will ensure that the applied adhesive will never rip or tear off the surface under the operational stresses.

Failure Modes

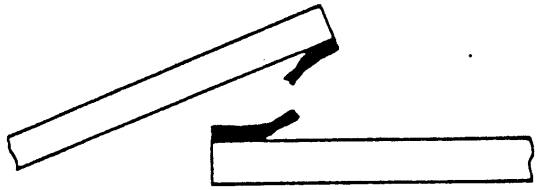
The ideal fracture during overload at an adhesive bond is either located in the adhesive layer and is thus a cohesion fracture or the joined material itself breaks in its cross-section.

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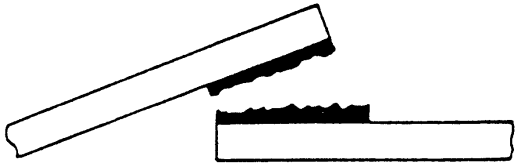
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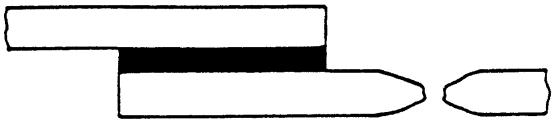
Bonded joint under tension load; elastically deformed.



Bondline cracking; adhesion crack.



Bondline cracking due to overload; normal cracking.



Good bondline behavior.

Figure 42 Typical Bonding Overloads

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Effects of Bond Thickness

General

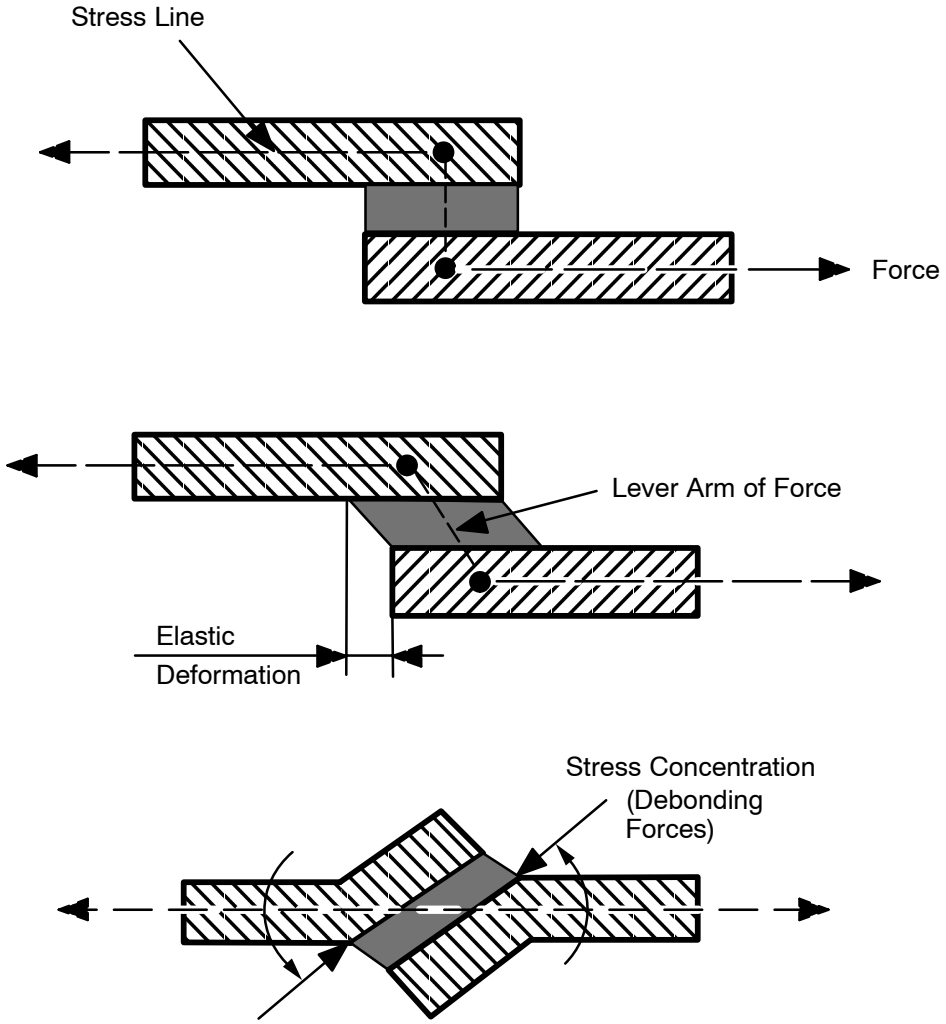
The thickness of the bond has great influence on the tensile shear strength of the bonded connection. In the case of a wide joint, the stress center line of the parts is far away from each other. When the connection is subjected to stress, the stress center line will move closer to each other, because the bond volume changes into a parallelogram form.

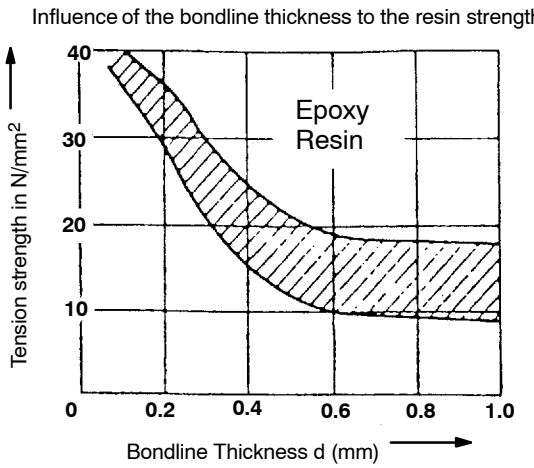
The larger the thickness of the joint, the more an overlapping connection of this kind is subjected to stress due to bending, and the stability of the connection will decrease in proportion to the thickness of the joint.

The thickness of the joint should not exceed 0.1mm in the case of bonded metal parts.

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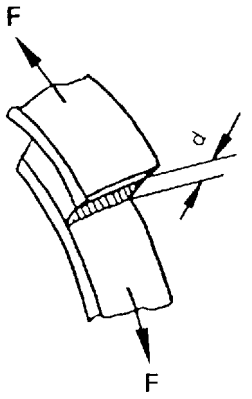


Figure 43 Influence of Bondline Thickness

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EFFECT OF OVERLAP LENGTH

Overlap of an Adhesive Bonding

By increasing the overlap and therefore the bonding surface, the maximum breaking load of the joint parts can be enhanced.

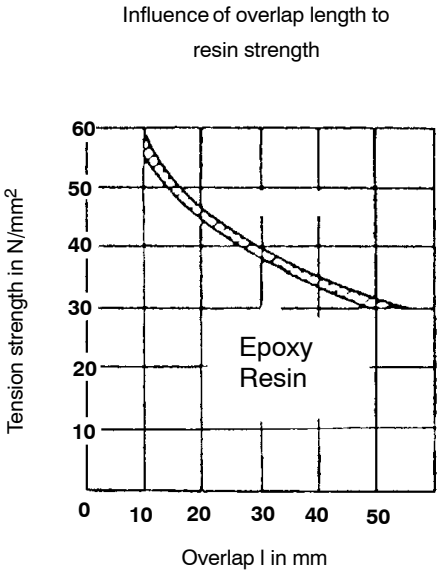
But the adhesive bond strength is decreased due to the stress concentration at the ends of the overlap.

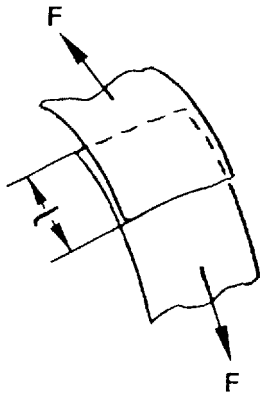
The bonding strength is not a material parameter that can directly be used for the determination of bonded constructions.

This parameter is rather used for comparative considerations, e.g. to investigate the effect of different surface pre-treatments.

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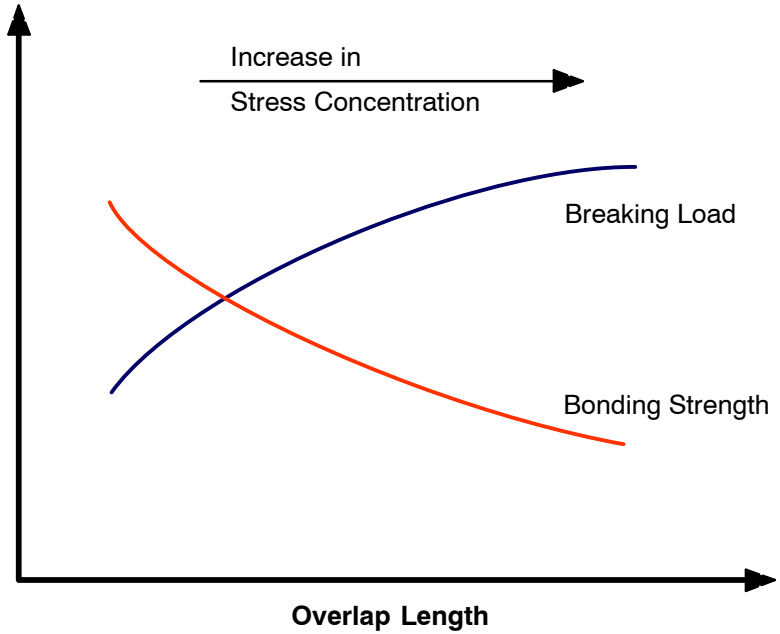


Figure 44 Effect of Overlap Length

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Design of Bonded Joints

General

If using adhesive bonding for joining mechanically stressed constructions, the high sensitive of bonded joints to peel stress has to be regarded.

Due to the, in comparison to metals, generally low tensile and shear strength of adhesives, large bonding surfaces have to be chosen, which result in low stress in the bonding.

Adhesive bonding should be designed in such a way that the joint is not stressed with perpendicular pulling forces.

1. Blunt Joints

This joint is not suitable for the transfer of forces because the bonding area is small and the strength of the adhesive will never reach the strength of the material of the parts. Unsuitable for airplane construction.

2. Single Lap Joint

This connection is preferred for thin cross sections in airplane construction, because of its easy realization.

3. Double-Fishplate Connection

This connection has a higher stability than the single-fishplate, but it requires more work and time. It is rarely used, because you cannot reach the condition of a smooth and even bonding connection on either side.

It is therefore hardly practicable for airplane construction.

4. Single-Fishplate

This connection is often used if a surface has to be smooth without any special pretreatment.

5. Shaft Connection

This connection reaches high stability values, but requires much work. Especially for performance under dynamic stresses, the shaft connection is superior to all other bonding connections.

It was widely used in wooden airplane construction, e.g. for glued spars.

In the cases of all described bonded connections with the exception of the shaft-connection, the connections require peel strength adhesives, because stress peaks occur at the end of material sections.

6. Reinforced Lap Joint

This connection is preferred for thin cross sections in airplane construction, because of its easy realization.

7. Bonded Reinforcement

Common in airplane construction, e.g. stringer or doubler and sheet metal skin.

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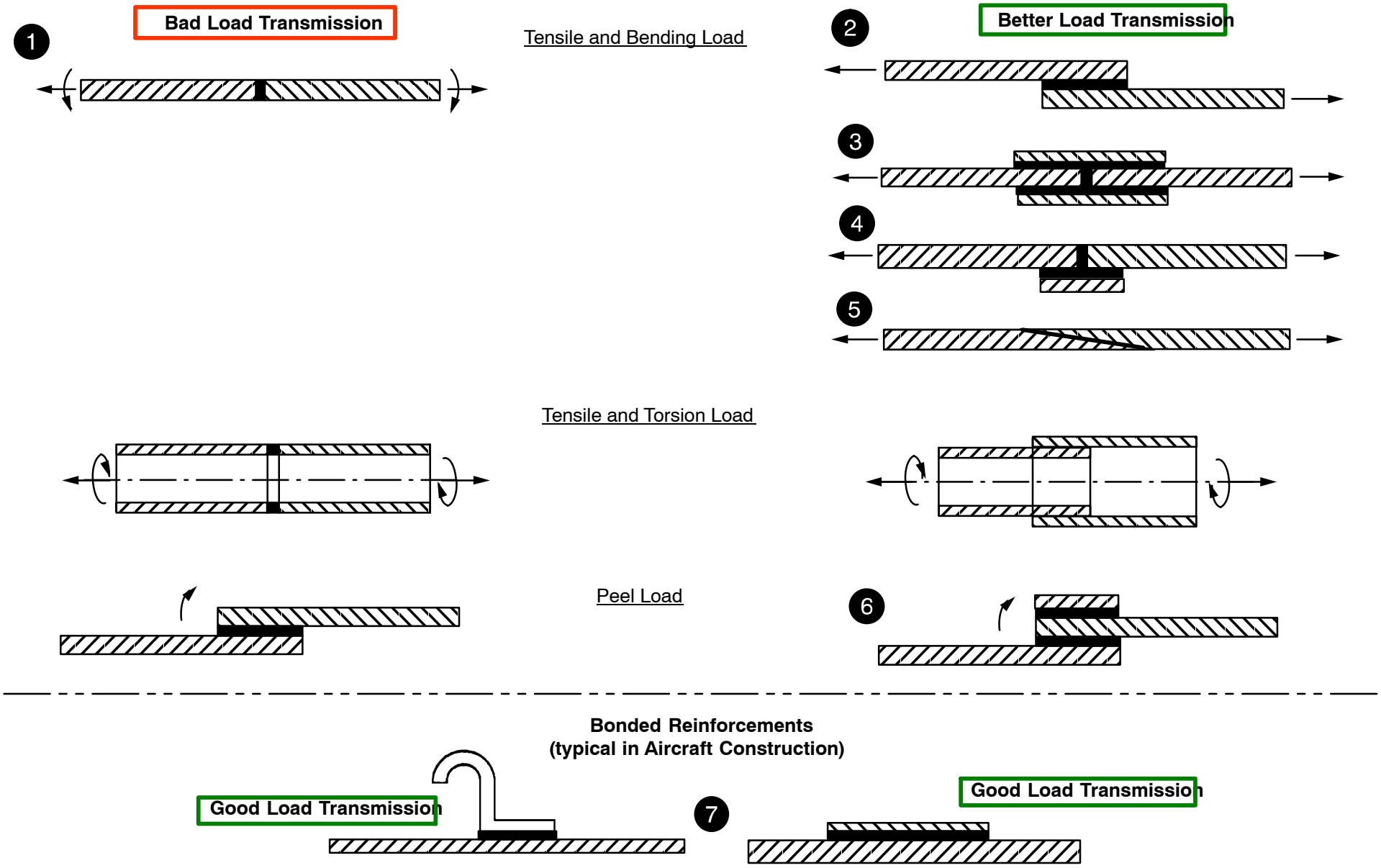


Figure 45 Design of Bonded Joints

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Stresses in Different Kinds of Connection

Rivet Connections

Peaks of stresses at the countersinks and their edges.

Welded Connections

Uneven distribution of stresses because of superimposed welding-stresses.

1. Weld
2. Overheat area
3. Hardened area

Bonded Single Lap Joint Connection

Shear-stress distribution results in extreme stress peaks at the edges of bonded parts.

Bonded Shaft Connection

Most even distribution of stresses.

Advantages and Disadvantages of Bonded Joints

Metal Bonding

Due to the development of well adhering, non-aging metal adhesives, it is possible today to join large areas of an aircraft with the help of adhesive bonding.

Adhesive bondings have the following advantages in comparison to rivet joints:

- lower concentration of mechanical loads,
- higher component stiffness,
- Better sealing (e.g. in pressurized cabin or fuel tanks),
- lower manufacturing costs,
- lower risk of contact or crevice corrosion,
- if joints are outside, improvement of the aerodynamic efficiency of the aircraft skin.

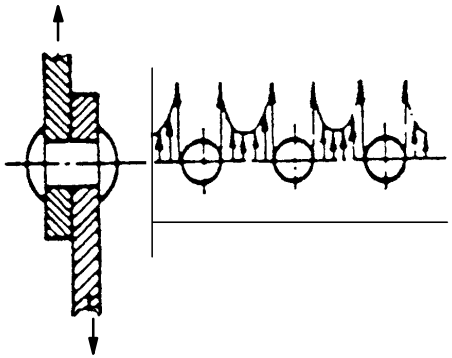
Bonded joints have the following disadvantages:

- relatively low mechanical strength,
- low heat resistance,
- highly sensitive to chemical reactions,
- highly sensitive to humidity,
- characteristic of adhesives to move into neighbor areas,
- non-destructive dissolving of joints not possible.

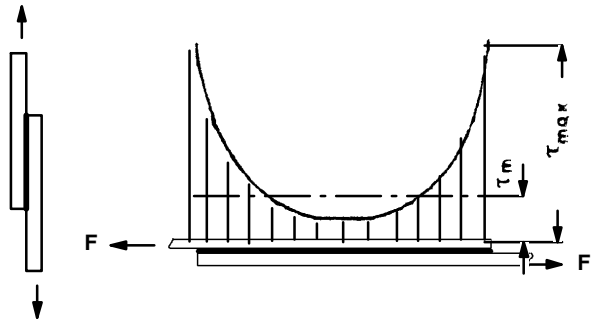
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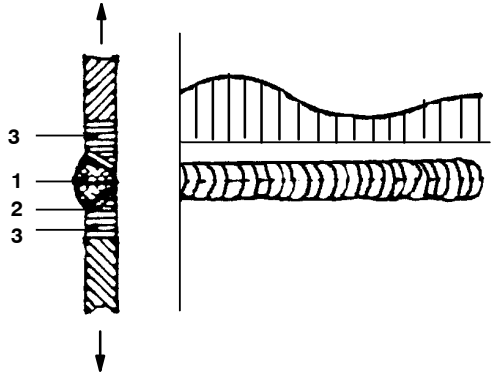
Rivet Joint



Single Lap Joint Bonding



Welded Joint



Bonded Shaft Connection

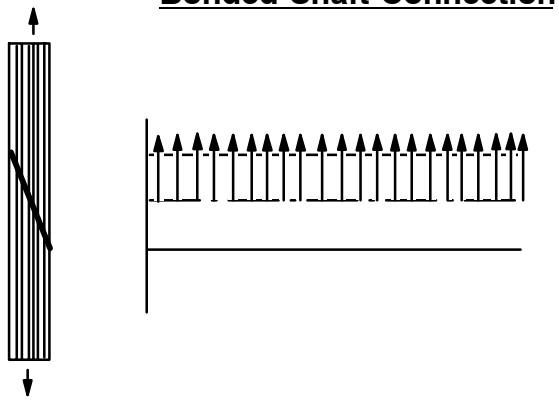


Figure 46 Stress Distribution

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Properties of Resins and Bonded Connections

Stability of Bonded Connections

There are some technological problems which have to be taken into consideration by the aircraft manufacturer when parts are to be bonded.

The most important differences between 2024 and 7075 aluminium alloys and epoxy-resin are the lower stability (breaking load) and the higher elasticity and thermal extension of the latter.

Aluminium that can be subjected to age hardening has a stability ten times as high as epoxy resin.

The elasticity under load and the temperature extension coefficient are 10 times higher than the respective values for aluminium.

As a matter of fact, several technical and physical factors have a strong influence on the construction of the bond.

These factors will lead to certain measurements. Often the shape and measurements will differ from those commonly used for rivet connections.

The following tables and diagrams show the most important factors the manufacturer has to keep in mind. Most data were determined empirically.

Generally, deviations from the specified instructions for repair procedures are not necessary for airlines, because the different work procedures, cure times, pressures, temperatures etc. depend on the results of the above-mentioned data.

Deviations often lead to worse results.

Only material that has been specified by the aircraft manufacturer is permitted for use in repairs.

Any modifications for which the airline is responsible will automatically lead to the expiration of claims under warranty which could result from the respective repair.

M A T E R I A L	**Rm** = KSI
Carbon Steel	from 50
High Strength Steel Heat Treated	up to 300
CRES	60 - 115
Ti 6Al 4V	up to 185
AA 2024	65
AA 7075	80
Epoxi - Resin	up to max. 15

When constructing the components, the respective safety factor and possible fatigue of the material have to be considered.

This means that the breaking load values are normally reduced by up to 75%.

In the case of composites, an additional safety factor of **j=1.5** is added according to FAR 25:

$$j_{kompl.} = j \times j_R$$

$$j_{kompl.} = \mathbf{1.5 \times 1.5 = 2.25}$$

The Shear-strength for EP-adhesives that cure with heat treatment (125 degree C-system) is thus calculated with

τ_B = 6,5 KSI

(15 KSI/2.25), but a number of flight-operational influences can reduce this value dramatically.

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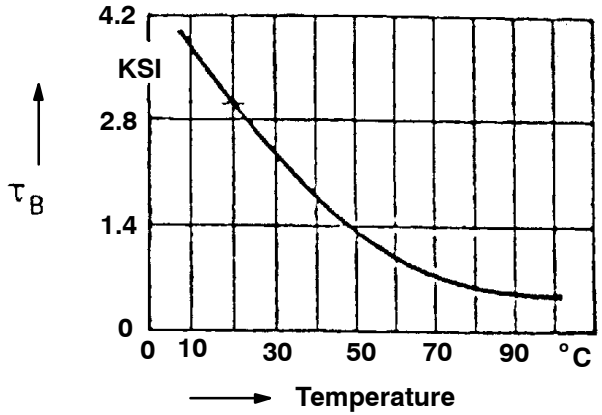
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Influence on adhesion caused by temperatures like permanent operational temperature or temporary solar radiation.



Comparisons of elasticity-modules

The E-module is the theoretical tensile stress that will expand a material-bar of certain length to twice this length:

E = Tension/Expansion

E - M o d u l u s	KSI
Steel	30.000
Titanium	20.000
AA 2024/7075	10.000
PF - Resin	1.370
EP - Resin	960
Sealing Compounds	70

INFLUENCES ON PRODUCTION

Curing Time

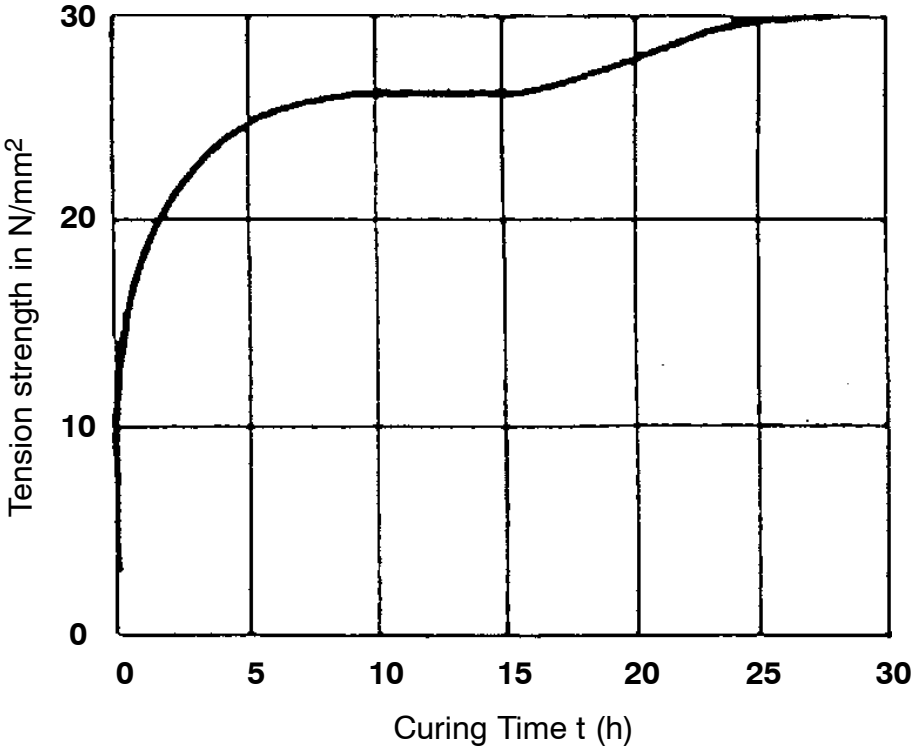
The consideration of curing processes during fabrication has highest priority. There is known data for the cure of cold age-hardening epoxy adhesives for a period of about 26 hours.

It is also known that, for acceptable periods, EP-adhesives actually require considerably higher temperatures to develop best adhesion values than are possible for the heat treated aluminium sheet metal parts.

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Curing time up to a tensile strength of 30 N/mm^2 for a room-temperature curing epoxy resin



Theoretical curing of epoxy resin according to the increasing curing temperature (oven or autoclave)

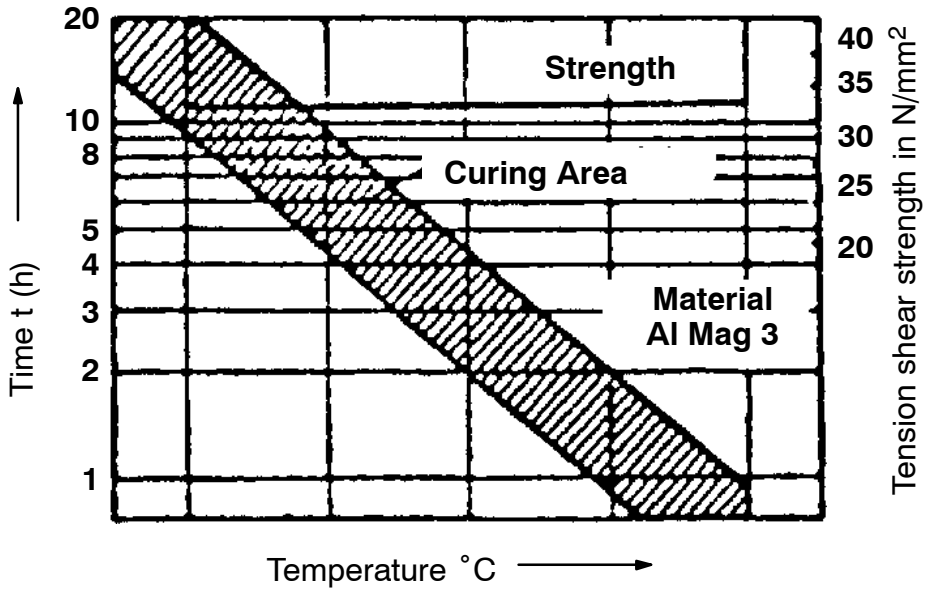


Figure 47 Curing Times

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EPOXY BONDING IN AUTOCLAVE

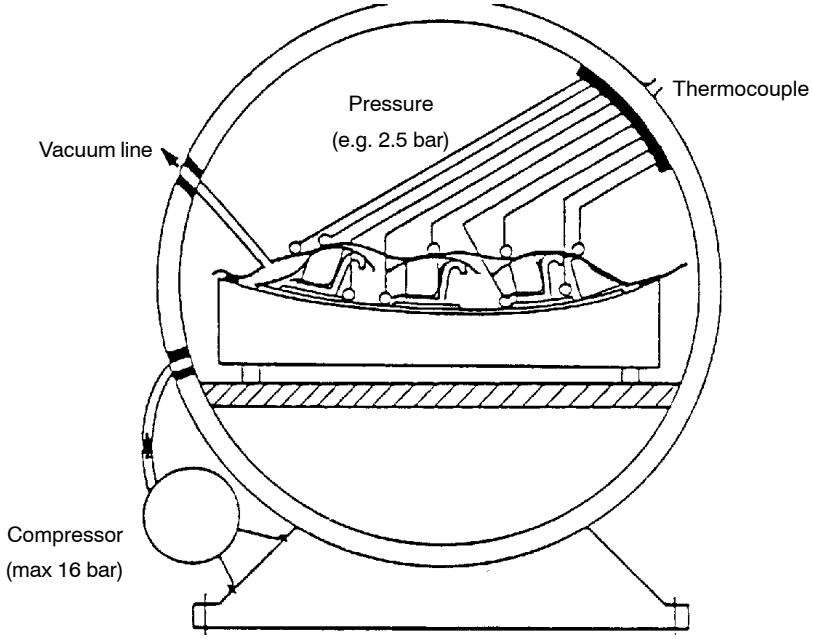
General

For the polymerization process, the EP-adhesion-film is mostly used in the autoclave at 2-3 bar overpressure and 125-175 degrees C.

At the same time, possibly enclosed moisture will evaporate and is removed by a vacuum (suction).

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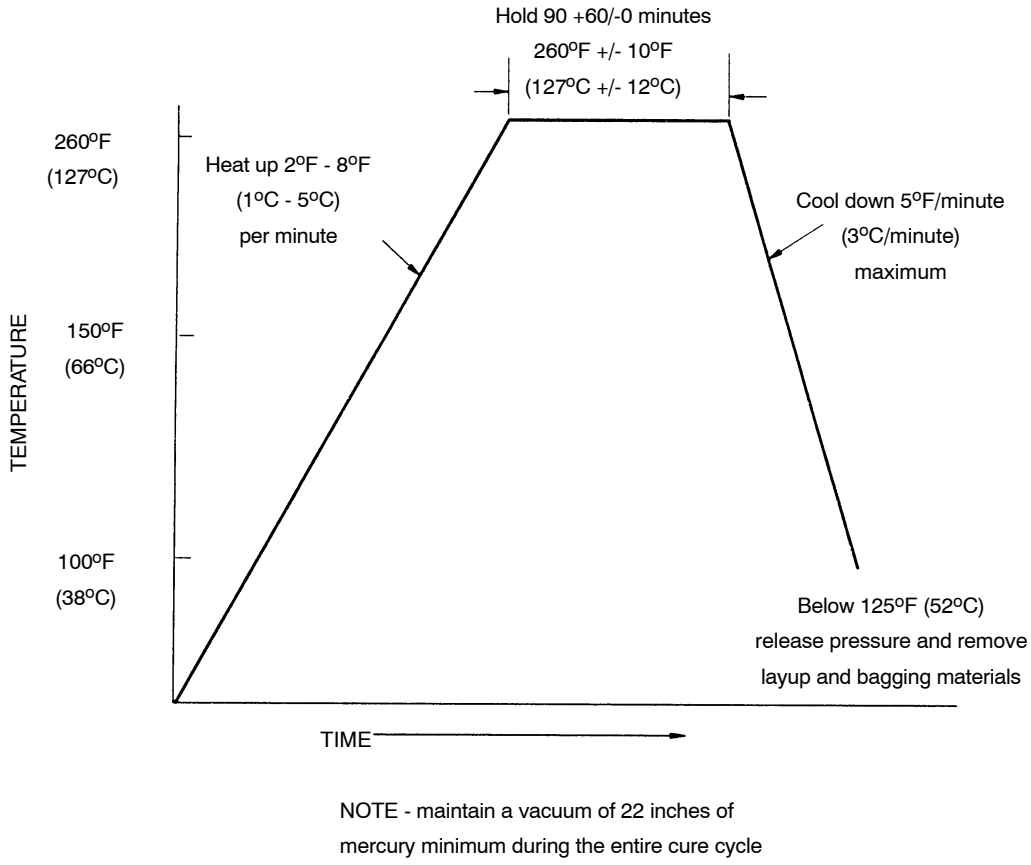


Figure 48 Bonding Process

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CHARACTERISTICS OF EPOXY RESINS ADHESIVES

Product	Form	Weight (g/m²)	Curing Temp °C	Curing Time H	Temp Stability °C	Tensile-Shear-Strength (N/mm²): Bonding Al Alloy Panels at R T
Araldite 123 B Hardener HY 956	Thickened fluid	200-400	+20 +60 +100	36 1 30 min	-60 to +70	12 to 15
Aradite 106 Hardener 953 U	Thickened fluid	150-300	+20 +40 +160	24 6 1	-60 to +60	12 to 25
EC 2216 B/A	Thickened fluid	200-400	+20 +60 +90	36 2 1	-60 to +70	22
Versamid 125 Epoxy resin BN 710	Fluid	100-500	+20	24	-60 to +70	10
FM 1000	Film	250	+175	1	-55 to +82	45
Metlbond Type I	Film	450	+175	1	-55 to +160	25
FM 96	Film	400	+175	1	-55 to +160	25
Redux 775	Fluid and powder	450	+150	30 min	-55 to +70	30
EC 2214	Thickened fluid	100-400	+120	40 min	-55 to +82	28
FM 123-5.03	Film	150	+125	30 min	-55 to +82	30

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